Atlantic salmon at sea:

Findings from recent research and their implications for management

Malcolm L. Windsor, Peter Hutchinson, Lars Petter Hansen and David G. Reddin. 2012. Atlantic salmon at sea: Findings from recent research and their implications for management. NASCO document CNL(12)60. Edinburgh, UK. 20pp.
Design & Layout: Peter Lloyd, Design Consultant, Edinburgh, UK.
Printer: 21 Colour Limited, Glasgow, UK.
Publisher: North Atlantic Salmon Conservation Organization (NASCO), 11 Rutland Square, Edinburgh EH1 2AS, UK.
ISBN: 978-0-95-9514129-1-6
Date of Publication: May 2012.
Contact: The Secretary, NASCO, 11 Rutland Square, Edinburgh EH1 2AS, UK. e-mail: hq@nasco.int

The 'Salmon Summit'

The North Atlantic Salmon Conservation Organization (NASCO) and the International Council for the Exploration of the Sea (ICES) are inter-governmental organizations. NASCO's objective is to contribute through consultation and cooperation to the conservation, restoration, enhancement and rational management of salmon in the North Atlantic Ocean. ICES coordinates and promotes marine research on oceanography, the marine environment, the marine ecosystem, and living marine resources in the North Atlantic.

In October 2011, NASCO and ICES Co-Convened the 'Salmon Summit', an international symposium entitled 'Salmon at Sea: Scientific Advances and their Implications for Management'. The objectives of the symposium were to:

- review recent advances in our understanding of the migration, distribution and survival of salmon at sea and the factors influencing them;
- consider the management implications of recent advances in understanding of the salmon's marine life;
- identify gaps in current understanding and future research priorities; and
- increase awareness of recent research efforts to improve understanding of salmon at sea and to encourage support for future research.

The 'Salmon Summit' was held in L'Aquarium, La Rochelle, France and was funded by NASCO's International Atlantic Salmon Research Board (IASRB) and ICES with sponsorship from the Total Foundation and additional support from The French National Agency for Water and Aquatic Environments (ONEMA). It provided a forum for presentation of the findings from the SALSEA Programme and other recent research on salmon at sea. One hundred and twenty-eight scientists and managers from around the North Atlantic, North Pacific and Baltic regions attended the symposium. While the focus was on research on salmon in the North Atlantic, the findings of recent research on Pacific and Baltic salmon were also presented. This report, by the Convenors of the 'Salmon Summit' and the Guest Editor of the 'Salmon Summit' issue of the ICES Journal of Marine Science, provides an overview of the research findings presented at the 'Salmon Summit' and considers the management implications of this new information. It is not intended to be a comprehensive report of all the presentations and discussions at the 'Salmon Summit'. More detailed information is available at www.nasco.int/sas/salmonsummit.htm.

FONDATION TOTAL

ONEMA

Contents

The Atlantic salmon ~ Lost at sea?

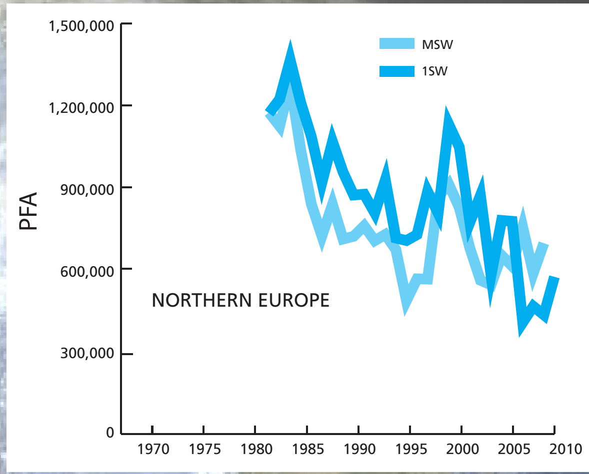
About 2,500 salmon rivers flow into the North Atlantic. Extensive research in fresh water has revealed much about the factors affecting juvenile salmon production, but considerably less is known about the life of salmon when they leave their home rivers and undertake their migrations in the North Atlantic Ocean. This lack of knowledge about the marine phase is partly due to the high cost of research on salmon at sea and the size of the North Atlantic.

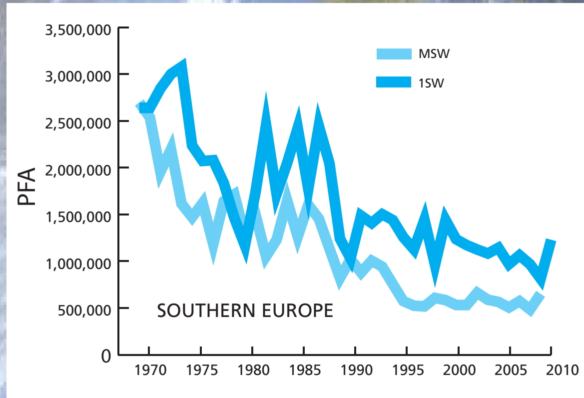
Reported catches for salmon in the North Atlantic from 1960 indicate that harvests peaked in the mid-1970s at about 12,000 tonnes, but have declined markedly to around 1,500 tonnes in recent years due to reduced abundance and the introduction of restrictive management measures in the fisheries. Catch data, together with estimates of exploitation rates and unreported catches and other information, are used to determine the abundance of salmon at sea before any fisheries (i.e. pre-fishery abundance or PFA). In providing management advice to NASCO, ICES uses three different stock groups: North America, Northern Europe (Russia, Finland, Norway, Sweden (west coast), and the northeast regions of Iceland) and Southern Europe (UK, Ireland, France, and the southwest regions of Iceland). Estimates of PFA are provided for both maturing and non-maturing one-sea-winter salmon. Maturing fish return to rivers to spawn after one winter at sea and are referred to as one-sea-winter (1SW) salmon (or grilse). Non-maturing fish return after two or more winters at sea and are referred to as multi-sea-winter (MSW) salmon.

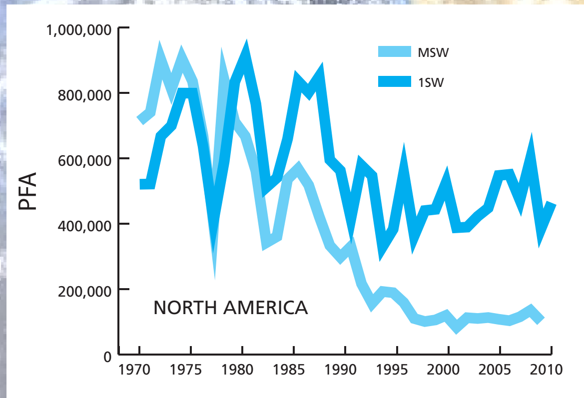
Over the last forty years, PFA has declined from about 10 million salmon in the 1970s to about 3.6 million in recent years. The decline in PFA since 1970 has been most marked for North American and Southern European stocks and for MSW salmon in particular.

	% decline in PFA	
Stock group	Maturing 1SW	Non-maturing 1SW
Northern Europe	49%	54%
Southern Europe	66%	81%
North America	40%	88%

Monitoring of rivers in Europe and North America indicates that marine survival has declined dramatically. In response to declining abundance, conservation measures have resulted in major reductions in fishing effort all around the North Atlantic and there is increasing use of catch and release in rod and line fisheries. The effect of these measures has been that the decline in spawners has been less marked than the decline in PFA. However, assessments based on stock groupings can mask trends in regions or individual rivers. While some rivers are performing well, many river stocks, in all three stock groups, are below their conservation limits (the spawning stock level below which recruitment i.e. the number of fish entering the population, will decline significantly). For example in 2009/10, only 59% of rivers in England and Wales, 43% of rivers in Ireland, 41% of rivers in Canada and 12% of rivers in France exceeded their conservation limits. The situation is particularly severe in the southern parts of the range. In North America, for example, the wild Atlantic salmon has been listed under the US



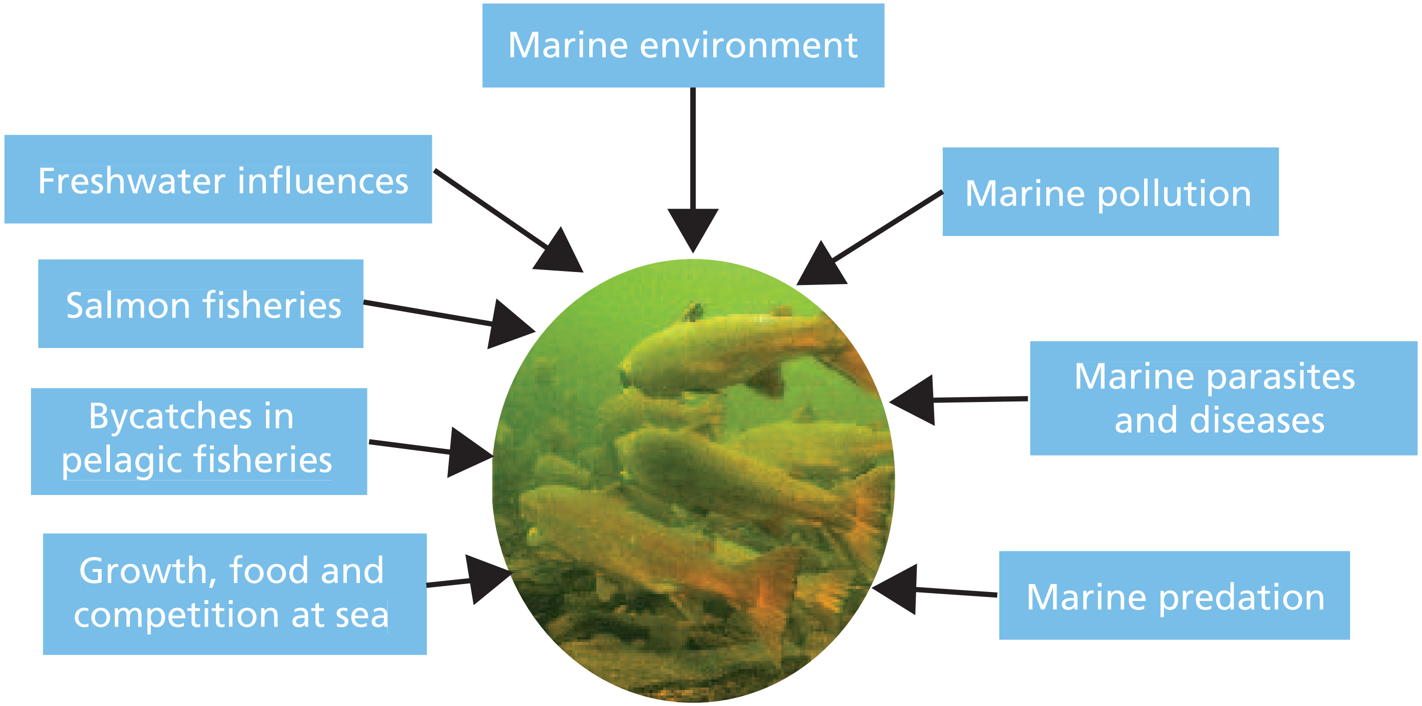




Graphs showing trends in pre-fishery abundance of salmon in the North Atlantic. Source: ICES

Endangered Species Act and some salmon populations in Canada have been listed under the Species at Risk Act.

Many factors (see Figure below), operating individually or in combination, may affect marine mortality of salmon or, if non-lethal, may affect traits such as growth and age at maturity. The challenge in understanding the causes of the increased mortality of salmon at sea is, therefore, substantial. For these reasons the SALSEA Programme was launched.



Factors that can affect the mortality of salmon at sea.

Monitoring facilities in salmon rivers in Norway (top) and Russia (bottom).

What is the SALSEA Programme?

Background

Increased mortality of Atlantic salmon at sea and a lack of understanding of the factors responsible undermine the conservation and restoration initiatives being undertaken around the North Atlantic and are obstacles to rational management. The numbers of smolts emigrating from, and the numbers of adults returning to, a network of monitored rivers around the North Atlantic provide a measure of marine survival. However, the factors influencing survival in the ocean remain a mystery.

In response to concerns about this increased mortality of salmon at sea, NASCO established an International Atlantic Salmon Research Board (IASRB) to promote collaboration and cooperation on research into the causes of marine mortality of Atlantic salmon and the opportunities to counteract this. By developing and reviewing an inventory of ongoing research (www.nasco.int/sas/research.htm), the Board decided that its priority was studies on the migration and distribution of salmon at sea in relation to feeding opportunities and predation.

A comprehensive new research programme

Only by better understanding where the salmon are at sea would it be possible to identify the factors influencing them. The Board, therefore, developed and supported an international programme of cooperative research on salmon at sea, the SALSEA Programme, taking advantage of recent advances in marine sampling, genetic techniques for stock identification, electronic tagging systems and scale analysis.

These advances provided an opportunity to begin to unravel the secrets of the Atlantic salmon's life at sea and to shed new light on the causes of its decline.

The SALSEA Programme combines a mix of freshwater, estuarine, coastal and offshore elements to provide a comprehensive overview of factors that may affect the marine mortality of Atlantic salmon. By sampling outgoing smolts, post-smolts, 1SW salmon at West Greenland and returning adults, SALSEA covered the entire marine phase. The Programme contained three main elements: Supporting technologies; Early migration through the inshore zone (fresh, estuarine and coastal waters); and Investigating the distribution and migration of salmon at sea.

Supporting technologies

The aim was to develop new technologies in support of marine surveys and included:

- identification of the region or river of origin of salmon sampled at sea through the development of genetic stock identification methods;
- enhancement of the efficiency of sampling of salmon at sea through the development of improved research gear; and
- identification of growth histories of salmon at sea through the development of methods of scale analysis.

Early migration through the inshore zone

The factors affecting mortality of salmon at sea include those operating in fresh water that influence the fitness of

emigrating smolts at sea or their ability to move from fresh to salt water (and back) and factors operating in the coastal zone. The aims of this research were to investigate the influence of factors in the inshore zone by examination of:

- biological characteristics (e.g. size) of salmon smolts;
- physical factors in fresh water (water flow and temperature);
- freshwater contaminants;
- predation; and
- salmon aquaculture.

Some of this research was already being undertaken by, or through partnerships with, national agencies. The role of the IASRB was to enhance coordination of the research and to stimulate additional financial support.

Investigating the distribution and migration of salmon at sea

The aims of this research were to conduct comprehensive, multi-disciplinary post-smolt surveys throughout the salmon's North Atlantic range. This was the priority under the SALSEA Programme. Limited efforts had been made to conduct such surveys prior to this Programme. The research involved:

- development of theoretical migration models to facilitate planning of the marine surveys;
- planning and implementation of marine surveys to collect information on migration patterns, distribution and factors affecting mortality of salmon at sea; and
- collation and analysis of the data.

Implementing the SALSEA Programme

The investigations relating to the distribution and migration of salmon at sea involved marine surveys in the Northeast (SALSEA-Merge) and Northwest (SALSEA North America) Atlantic and an enhanced sampling programme (over and above the long-term ongoing sampling) of the internal-use fishery at West Greenland (SALSEA West Greenland). Additionally, the IASRB supported studies to re-examine historical tag recovery data from distant-water fisheries and to investigate associations between changes in biological characteristics of Atlantic salmon, environmental changes and variations in marine survival.

Further information on the SALSEA Programme is available at www.nasco.int/sas/salsea.htm.

SALSEA-Merge

The objective of SALSEA-Merge was to advance understanding of stock-specific migration and distribution patterns and the ecology of salmon at sea. This was done by merging genetic and ecological investigations in order to gain insights into the causes of the increased marine mortality. This three year project was supported by the European Commission under the Seventh Framework Programme for Research and Technological Development. Additional funding was provided by the Partner organisations including the Total Foundation (France) and the Atlantic Salmon Trust (UK). The project was launched in May 2008 and involved a consortium of twenty research and other organizations from nine European countries.

Marine surveys in the Northeast (top) and Northwest (bottom) Atlantic.

Marine surveys were conducted by Irish, Faroese and Norwegian research vessels in both 2008 and 2009 to collect salmon and environmental information. New genetic databases were developed and the region, or river, of origin of the sampled fish was determined using the latest genetic stock identification techniques. Patterns of growth were determined for both contemporary and archived scale samples and food and feeding patterns were studied. A unique biological and environmental database was developed to facilitate future analyses. In addition, the Regional Ocean Modelling System, which merges hydrographic, oceanographic, genetic and ecological data, was used to develop novel stock-specific migration and distribution models.

Further information on the SALSEA-Merge project is available at www.nasco.int/sas/salseamerge.htm.

SALSEA North America

The SALSEA North America project involved life-history studies, acoustic tracking and marine surveys. Monitored rivers in eastern North America provided data on life-history, feeding, disease and parasite status and marine mortality and its causes.

Acoustic tracking studies involved implanting miniaturized acoustic transmitters in salmon smolts and kelts which were detected by listening stations at various points along the migration route, up to 800 to 1,000 km from home rivers.

The marine surveys involved sampling the early post-smolt phase (August to October) with near-surface trawls and gill nets. Surveys were conducted in 2008 and 2009 by Canadian vessels and provided information on the relative abundance and distribution of salmon within the pelagic ecosystem in relation to other fish species and oceanographic conditions.

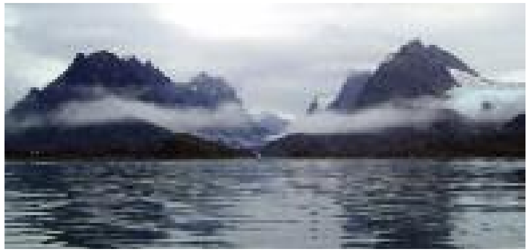
Further information on SALSEA North America is available at www.nasco.int/sas/salseaamerica.htm.

SALSEA West Greenland

MSW salmon from both Southern Europe and North America occur at West Greenland so a new sampling programme of the internal-use fishery, to enhance the existing long-term sampling, was developed. The aim was to increase the nature and extent of sampling and integrate it with SALSEA-Merge and SALSEA North America to further improve understanding of salmon at sea. The samples obtained were used to study, for example, age and growth, diet, origin, lipid content, and parasite and disease status.

In 2009, 2010 and 2011, whole fresh fish were obtained from the fishermen for scientific analysis. These fish were part of the existing internal-use fishery and not additional to it. Paramount to the sampling programme was the ability to identify the origin of each individual fish to region or river of origin through genetic analysis to enable comparisons of marine survival between different stock groups.

Further information on the SALSEA West Greenland project is available at www.nasco.int/sas/salseawgreenland.htm.



Deploying detectors for acoustic tags in Chaleur Bay, Canada (top), the landscape at West Greenland (middle) and sampling salmon caught in the internal-use fishery at West Greenland (bottom).

What did we learn from the 'Salmon Summit'?

The SALSEA Programme and other recent research have generated very large amounts of new data some of which was presented at the 'Salmon Summit'. Full analysis of these data is ongoing and will lead to a clearer understanding of the ecology of Atlantic salmon at sea and should support future management, but it may take some years before it is complete. Other information, e.g. on plankton, parasites, lipids, etc. has been collected and is available for future analysis if funding becomes available. We do not yet have the benefits of all the research conducted. However, much has already been learned and this is summarised below. Wherever possible, scientific language has been avoided and this may have resulted in over-simplification. More detailed information, including the presentations made at the 'Salmon Summit', is available at www.nasco.int/sas/salmonsummit.htm.

The changing environment in the North Atlantic

Salmon occupy freshwater, estuarine and marine environments during their life-cycle. Factors influencing salmon mortality in these different habitats do not operate independently and changes in one habitat could result in increased mortality in another.

Freshwater environment

Climate change is a concern in the freshwater environment because predicted temperature rises over land are higher than at sea. Increased climate variability could change flow patterns (including the frequency and intensity of floods and droughts) and consequently affect water quality.

Marine environment

During the 21st century, the temperature of both the ocean and the atmosphere are expected to increase. Most climate models also predict changing ocean circulation in the North Atlantic, although the regional effects are uncertain.

Long-term changes in North Atlantic salmon are associated with this warming. Marine ecosystems, e.g. in the Northeast Atlantic, have responded by a shift to a warmer regime and there have been marked changes in the composition and production of plankton and salmon abundance in the North Atlantic, particularly since the late 1980s. There is also evidence that some prey species of high nutritional status to the salmon have been replaced by species of lower nutritional value.

A northward movement of some fish species, including Atlantic salmon, and plankton species that are important prey of salmon, has been detected in the North Atlantic and appears to be linked to warming. Further changes in the ocean currents and climate of the North Atlantic are anticipated, but predictions of the nature and extent of these changes are uncertain as are their influences on salmon populations.

Salmon abundance and survival

North Atlantic salmon

Marine survival of salmon in the North Atlantic has declined and remains low. Common patterns of decline in abundance of Atlantic salmon suggest that factors operating over large

geographical areas are affecting productivity and abundance of salmon. The decline in abundance is greatest for MSW salmon in southern areas.

There could be a range of potential impacts on salmon from a changing climate including the extinction of some populations in more southerly areas. In North America, the southern edge of the range of Atlantic salmon is known to have shrunk by 2 degrees latitude (approximately 140 miles) and some salmon populations in the US and Canada are classified as endangered or at risk. However, climate change may affect local environments differently. In some rivers, higher temperatures have already been shown to increase growth rates, resulting in younger smolts and earlier migration to sea. This could result in smolts going to sea when ocean conditions are poor for growth and survival, i.e. a mismatch in run-timing. Contaminants in freshwater can also affect subsequent survival of salmon at sea and changing flow patterns in rivers might worsen these impacts.

Comparisons with Baltic and Pacific Salmon

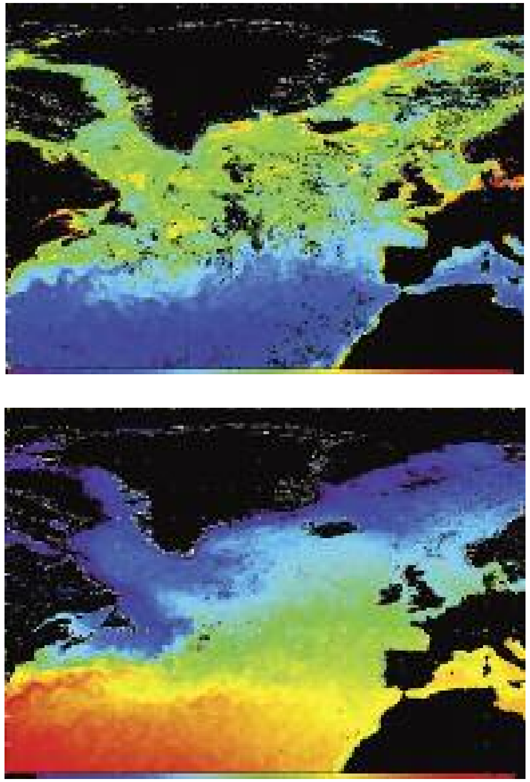
It is informative to consider the situation facing salmon in other areas. For example, Baltic salmon are also experiencing increased marine mortality, partly linked to grey seal predation of post-smolts and the availability of suitably-sized prey e.g. herring. In contrast, in recent years salmon production in some areas of the North Pacific has been at, or near, record highs, particularly for pink and chum salmon. However, as in the North Atlantic, some southern stocks are experiencing low abundance. In 2009, returns of sockeye salmon to the Fraser River (Canada) were the lowest since 1948. However, the following year the returns were among the highest recorded. This extreme variability in returns was attributed to a combination of variable spawner abundance and variable oceanic conditions and highlights the importance of maintaining freshwater production so that the salmon can benefit from any improvements in ocean conditions.

Distribution and Migration of Salmon at Sea

Marine migrations of salmon may vary among stocks and affect their mortality at sea. There have been major advances in our understanding of the differences in distribution and migration among stocks of salmon in the North Atlantic through a variety of research methods including acoustic tags, archival tags, marine surveys (the findings from which are presented in various sections that follow), re-examination of tag recovery data, genetic stock identification, migration models and stable isotope analysis.

Acoustic tags

Acoustic tracking provides a reliable and effective means of deriving quantitative estimates of survival of salmon at various points along their migration routes far out to sea and could form an important input to future stock assessments. In Canada, smolts originating in five rivers have been tracked through the Gulf of St Lawrence as far as the Strait of Belle Isle (between the northern tip of Newfoundland and mainland Canada). The study found that the highest mortality rates for smolts occurred in the estuary or freshwater. The timing of migration of smolts from the different rivers was synchronised and smolt migration was



Images of the North Atlantic taken from NASA's Aqua satelite showing the chlorophyll concentration (top) and sea surface temperature (bottom) in May 2010.

synchronised with that of kelts. This led to an interesting suggestion that smolts may 'learn' migration routes from kelts. Travelling in groups may also be an important survival strategy because of 'predator swamping' and 'predator confusion' effects.

In Canada, acoustic tagging of kelts indicated that residence time in the estuary was short and survival high. After a short period regaining condition, some of the tagged kelts returned as consecutive-year repeat spawners while others over-wintered in the Atlantic before returning as alternate-year repeat spawners.

Archival tags

Archival tags store data such as timed temperature and depth information that may be transmitted to satellites or recovered when the fish are recaptured.

Tagging kelts in Norway, Ireland, Denmark and Iceland and non-maturing 1SW salmon at West Greenland with satellite archival tags has provided valuable new information on the distribution and migration of salmon and the causes of mortality. For example, while the various populations tagged used different migratory routes, all fish moved with oceanic currents and gyres (large systems of rotating currents) and were consistently found in proximity to polar fronts (areas where cold Arctic water meets warm Atlantic water) far to the north (up to 80°N). Regular dives ranging from 400 to 900m were detected.

Archival tags applied to kelts in the Campbellton River, Canada indicated that salmon were frequently present at depths of more than 5m and spent less time at the surface during the day than at night, possibly indicating a reliance on vision for feeding at depth. There may be an energetic advantage to salmon in diving into cooler, deeper water where suitable prey are more abundant and then moving back into warmer water where digestion will be rapid.

Re-examination of tag recovery data from fisheries in the North Atlantic

Tags recovered from the distant-water fisheries at West Greenland and the Faroe Islands over a fifty year period have been newly combined, compiled, analysed and used to examine the distribution and growth of salmon of different origins and sea ages in time and space over that period. Tag recoveries at West Greenland indicate that North American salmon have a more northerly distribution than European origin salmon. In the Northeast Atlantic, MSW salmon from northern Europe appear to have a more easterly distribution than those from southern Europe and tags from northern Europe and the US were more frequently recovered at East Greenland than tags from other countries. Around the Faroes, a significant proportion of salmon caught in the late Autumn originated from southern European countries while fish from northern regions were more abundant in the winter period.

In the period 1962 - 1992, more than 1.5 million salmon, mainly hatchery-reared smolts, were tagged and released in the US tagging programme. More than half of the recoveries were in US waters, mainly as river returns, with the rest approximately equally split between distant-water fisheries

Tagging adult salmon to assess exploitation rates in fisheries.

in Canada and Greenland.

Genetic stock identification

During the SALSEA-Merge project, a new genetic database was established comprising information from approximately 27,000 individual fish from 284 rivers representing ~85% of non-Baltic European salmon production. This new tool was created to assist in identifying stock-specific migration and distribution of salmon at sea and has been used to investigate the geographical structuring of European Atlantic salmon stocks. These stocks were shown to be genetically divided into three well-defined geographical groups (Iceland; Scandinavia and Northern Russia; and mainland Europe, Britain and Ireland) with finer-scale regional structuring apparent within all groups. Assignment of salmon caught in the marine surveys in the Northeast Atlantic shows that salmon differ in their distribution patterns. For example, as no Icelandic fish were caught in these surveys, it suggests that they may migrate to unsurveyed areas to the west. Similarly, the absence of salmon from Finnmark and Russia suggests migration to the north of the area surveyed.

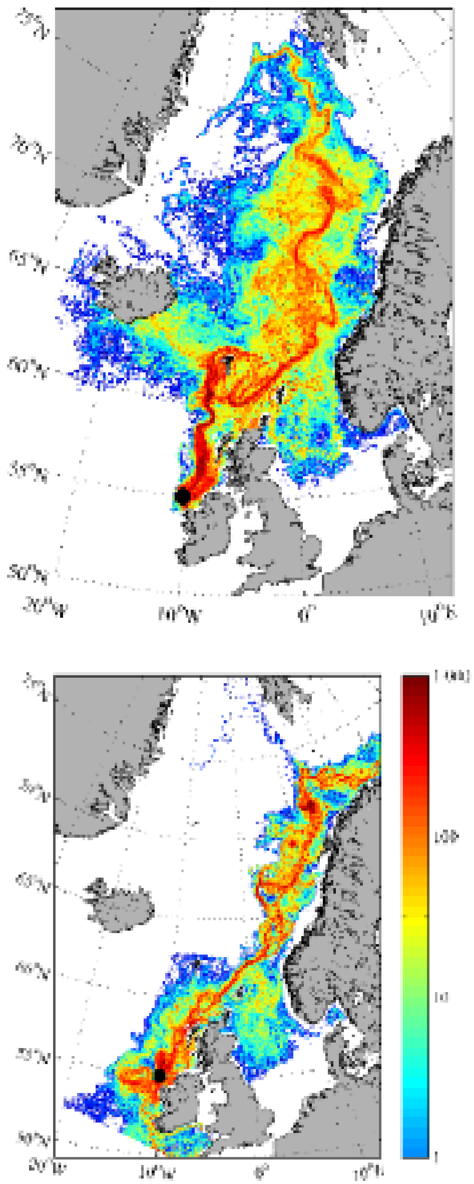
Other genetic techniques offer potential as cost-effective methods to provide both regional and finer-scale (river of origin) assignments. A preliminary study identified major clusters among the populations sampled which were comprised of Iceland, Northern Norway/Kola peninsula/White Sea, Western Norway/Sweden, Denmark/British Isles/Northern France and Southern France/Spain.

These new genetic tools, not unlike the DNA tools used in forensic science, should enable the origin of salmon at sea and in fisheries (including bycatch) to be determined. They could also facilitate identification of escaped farmed salmon.

Migration models

A migration model combining oceanographic and swimming speed data was developed that simulated the migration of post-smolts from the west of Ireland and the south-west of Norway in their first months at sea and was validated against observations of distribution from surveys. This provided useful information on likely migration routes, post-smolt distribution in time and space and differences between the two simulated stocks. In some areas along the migration routes, the direction of migration was found to be sensitive to annual changes in wind strength. The model could be used to investigate impacts of climate change on migration and distribution of salmon at sea.

A different model was used to examine the growth and survival of post-smolts migrating north from the US. This model combined ocean-circulation and bioenergetics (i.e. the flow and transformation of energy in salmon) and determined post-smolt mortality during their migration under different hydrographic conditions. The model could be refined by the inclusion of other factors affecting salmon survival (e.g. changes in predators and availability of prey as well as climate change scenarios) individually or in combination. The model results showed that between 60% and 100% of post-smolts could have survived the early stages of migration to a point off Halifax, Nova Scotia more than 500km away, depending on the currents experienced.



Output from models simulating the movement of 50,000 post-smolts from a 'release point' to the west of Ireland in 2002 (bottom) and 2008 (top). The colour scale represents the concentration of the post-smolts.

Stable isotopes

Isotopes are variants of the same chemical element. Nitrogen isotope composition in tissues of pelagic marine fish is strongly linked to their position in the food web and, therefore, to the size of the fish. Carbon isotope composition depends on the plankton communities at the base of the food web and can be used to investigate the approximate locations of fish at sea. A study based on archived collections of salmon scales from two rivers and a mixed-stock fishery in England indicated that adult fish from different rivers fed in different oceanic regions prior to their return and that 1SW salmon are separated from MSW fish in their marine feeding areas. Furthermore, the sampled salmon were not feeding in regions of the Northwest Atlantic frequented by 1SW salmon from rivers in Newfoundland.

Bycatch of salmon in marine fisheries

In the Norwegian Sea, the distribution of post-smolts overlaps with the mackerel fishery in international waters in the second and third quarters of the year. In the late 1990s, post-smolts and mackerel were caught together in June and July in Norwegian research surveys using surface trawls. There were also reports of adult salmon being caught in fisheries targeting herring in the northernmost part of the Norwegian Sea. Estimates developed in 2004/2005 of the bycatch in the mackerel fishery ranged from 0.0002 to 5.93 post-smolts per tonne of mackerel, depending on the source of the data (commercial versus research vessel). This resulted in very large variation in the estimated number of post-smolts caught (from a few individuals to 1.8 million fish).

Since these estimates were made, new information from national catch screening programmes in Iceland and the Faroe Islands has become available. Information from Iceland indicated bycatches of 4.8 and 7.0 salmon per 1,000 tonnes of mackerel and herring in 2010 and 2011 respectively, or approximately 169 and 200 salmon in total for the fishery. In the case of the Faroese mackerel fishery, bycatches of up to 37 salmon per 1,000 tonnes were estimated in some months for a total in the fishery of about 180 salmon in 2011.

While some fisheries for pelagic species do not appear to result in significant bycatch of salmon, there is great uncertainty in the estimates. Screening large pelagic catches for small post-smolts must be like looking for a needle in a haystack. Furthermore, the estimates do not take into account any additional sources of mortality of salmon such as that associated with the fishing gear but not included in the catch, e.g. fish that may be damaged but escape from the nets. The gear used in these pelagic fisheries is large and covers extensive areas of the sea during fishing. Because of the methods used, many of the figures generated represent minimum estimates and the real extent of the bycatch may be much higher. The quantification of bycatch remains challenging.

Food Production, Growth, and Ecological Interactions

Diet of salmon at sea

Recent studies have confirmed the importance of small fish in the diet of post-smolts in coastal waters and of amphipods (shrimp-like animals) in offshore waters in both the Northeast

Haul of mackerel made during a Norwegian marine survey (top) and a post-smolt and a mackerel caught in a pelagic trawl (bottom).

and Northwest Atlantic. In the Northeast Atlantic, post-smolts fed closer to the surface than herring and mackerel. In the Northwest Atlantic, the amount of food in the stomachs of post-smolts was less in the winter of 2008/09 than 2002/03. The diet of 1SW salmon at West Greenland was dominated by capelin, amphipods and squid.

Stable isotope analyses indicated that the diet of salmon returning to rivers in the UK becomes more focussed on prey higher in the food web as they increase in size. For Canadian salmon populations, such studies indicated that there is considerable variation in the diet of post-smolts, but much less variation in the diets of 1SW and 2SW salmon.

Growth of salmon at sea

Studies on an Irish salmon stock indicated that growth in the first year at sea was high during 1963 to 1981 and generally poor after this period particularly in recent years. This poor growth was correlated with low marine survival estimates for this stock. Growth and survival of salmon are influenced by environmental conditions at sea, including sea surface temperature. Comparison of post-smolt growth rates based on samples collected during the marine surveys in the Northeast Atlantic for four years in the period 2002 - 2009 showed that growth rate was lowest in the most recent years.

For some North Atlantic salmon stocks, both abundance and physical condition of fish returning to spawn have declined. Both 1SW and 2SW salmon returning to Scotland have shown a marked decline in condition, caused by changes in the marine environment which may have implications for both the number and quality of eggs produced. Furthermore, this decline in condition appears to be associated with a change in run-timing of 1SW salmon returning to Scottish rivers, with fish presently remaining at sea longer although in other parts of the North Atlantic there has been a shift in run-timing to earlier in the year.

In the Miramichi River, Canada there has been a marked increase in the number of repeat spawning salmon following closure of commercial salmon fisheries. There has been an increase in both consecutive- and alternate- year repeat spawners, with implications in terms of egg production and quality. Consecutive-year repeat spawners differ in that egg diameter and survival do not follow the general trends of increasing with female size. The increase in return rates of repeat spawners was related to the biomass of small fish in the reconditioning year at sea, suggesting that prey availability influences adult fish survival.

Recruitment

North American and European salmon respond to warming ocean conditions in different ways at different stages of their life history. Southern North American post-smolts are entering a warmer ocean, with different predator species and higher predator abundances, suggesting that recruitment is controlled by changes in predation pressure associated with the warmer conditions. For southern European stocks, marine survival and adult recruitment depend on post-smolt growth, particularly during the summer and early autumn period and declining marine survival is linked to warming conditions in the Northeast Atlantic during this period. Ocean

Salmon of different condition; 24% underweight (top) and 3% overweight (bottom) for their length.

Planktonic food items of the Atlantic salmon at sea.

temperatures in areas important to post-smolts are expected to continue to increase, with the possibility that marine survival will be unsustainable for some North American and European stocks.

Parasite burdens

Approximately 60% of the salmon sampled in the Labrador Sea during the SALSEA North America marine surveys were infested with intestinal parasites, some heavily, with prevalence generally higher in adults compared to post-smolts. High internal parasite loads could result in increased mortality of salmon.

Further research

There have been important advances in our understanding of the biology of Atlantic salmon at sea as a result of the SALSEA Programme and other recent research. Full analysis of the findings will assist in the identification of future research needs to support further advances in rational management of Atlantic salmon populations.

It seems unlikely that a coordinated research programme of this scale, dedicated only to salmon, in particular the marine surveys conducted under SALSEA-Merge and SALSEA North America, will be undertaken again in the foreseeable future given constraints on research budgets. However, national jurisdictions engage in annual sampling programmes in both the Northwest and Northeast Atlantic in order to collect data on the health and status of marine resources. Atlantic salmon are rarely captured in these programmes, not least because of the gear used. Opportunities to incorporate salmon sampling gear into these programmes should be explored as a source of additional data on the salmon at sea that could be obtained at relatively low cost. It will certainly also be valuable to maintain the links across research disciplines that have been established through the SALSEA Programme.

A major output from the SALSEA Programme has been the establishment of new databases and sample collections, not all of which have been fully analysed. New genetic databases have been created and further development and use of this information will assist management. A publicly available database integrates all of the data collected and analysed during the SALSEA-Merge project and serves as a repository for Atlantic salmon data, potentially including both European and North American data in the future. Further analysis of the data should add to our knowledge of salmon at sea.

Monitoring programmes in fresh water provide essential information on the status of salmon populations and trends in marine mortality and allow assessment of biological responses to environmental change. It is essential that they be maintained. Further studies are needed in fresh water to investigate links between smolt size and adult recruitment, the extent and significance of any mis-match between the timing of smolt emigration and ocean productivity and the effects of contaminants at a population level.

Acoustic tagging can provide quantitative estimates of survival at different points along the migration route and consequently aid in assessing where additional management actions might be targeted.

Sampling in the Northeast Atlantic during the SALSEA marine surveys.

What are the implications for salmon management?

The information presented at the 'Salmon Summit' has provided new insights into the factors controlling salmon abundance around the North Atlantic. It is clear that the increased marine mortality linked to a warming environment poses significant challenges and uncertainties for management.

Many salmon stocks are already below, or far below, their conservation limits. NASCO has agreed that in these circumstances stock rebuilding programmes should be developed. While the short-term response to a stock failing to achieve its conservation limit may be to reduce or eliminate fishing, overharvesting may not be the cause of the decline. In fact, given the controls on fisheries that have been introduced in many jurisdictions around the North Atlantic in response to declining abundance, there may be only limited opportunities to respond to further declines through management of the fisheries, as these have already been closed or greatly reduced.

The clear message from the 'Salmon Summit' in this challenging global environment is to maximise the number of healthy wild salmon that go to sea from their home rivers, since management options in the ocean are limited. This will entail addressing all the impact factors in fresh, estuarine and coastal waters including degraded freshwater habitat, barriers to migration, over-exploitation and salmon farming. Managing salmon in the face of the uncertainty about future environmental changes will be challenging. The goal should be to protect the genetic diversity of the wild Atlantic salmon in order to maximise their potential to adapt to the changing environment. Consistent with a Precautionary Approach, where there are uncertainties there is a need for caution. The absolute priority should be to conserve the productive capacity of the resource. The challenges will be most marked in the southern part of the salmon's range where the predicted warmer climate may lead to the extinction of some salmon populations. These stocks are important as they are adapted to warmer conditions. Continuing actions to conserve and rebuild them are to be encouraged. The actions taken will depend on social, political and economic factors in individual jurisdictions. Protection of salmon habitat in these areas will enable recolonization in the event that the warming conditions are reversed. On the other hand, there may be a northward expansion of salmon into areas that they do not currently occupy, such as parts of Labrador, southern Greenland and Svalbard. There may also be increased production in northern rivers currently supporting salmon populations, for example, as a result of a reduction in smolt age. Managers may be able to exploit these trends.

Here we look at the implications for salmon management of the new information from the 'Salmon Summit' by examining each of the factors influencing marine mortality (see Figure on page 2).

Marine environment

The warming ocean environment and changing currents are global issues, beyond the powers of salmon managers. The opportunities to manage salmon in the marine environment are limited so the focus will inevitably be on factors operating in fresh, estuarine and coastal waters.

Understanding how the changing marine environment affects salmon at sea may allow managers to adopt more appropriate measures. In the North Pacific, the benefits of maintaining spawning stocks have been highlighted in order to allow rapid stock rebuilding when oceanic conditions improve.

Salmon fisheries

Over the years since NASCO's establishment, major restrictions on exploitation of salmon have been introduced all around the North Atlantic in response to declining salmon abundance. The Northern Norwegian Sea salmon fishery was prohibited by the NASCO Convention which created an enormous protected zone, free of all salmon fisheries in most parts of the North Atlantic beyond 12 nautical miles of the coast. The distant-water salmon fisheries at West Greenland and around the Faroe Islands have been reduced through regulatory and other measures to internal-use only harvests or no harvest at all in most years since the late 1990s; a reduction of 99% from the peak harvests in these fisheries in the late 1960s and early 1970s. Fishing in international waters by vessels registered to non-NASCO Parties was addressed quickly through diplomatic channels when it occurred. States of origin have also introduced measures that have greatly reduced fishing effort. Catch and release in rod and line fisheries is increasingly used. Further information on the management of salmon fisheries is available at www.nasco.int/fisheries.html.

It will be important to respond rapidly if fishing for salmon in international waters recommences in the future. It is also important to maintain measures for the distant-water fisheries based on scientific advice on abundance. In this regard both the Faroe Islands and Greenland have shown great restraint in limiting harvests but their willingness to do so in the future may depend on whether they consider that equivalent measures are being undertaken by States of origin. Information derived from analysis of historical tag data may be useful in the future management of the distant-water fisheries although the current validity of the information will need to be confirmed. In some years, there are harvests of salmon reported from East Greenland so conservation measures may be needed.

Rational management of salmon fisheries involves the establishment of conservation limits to define adequate levels of abundance for each river. This process is ongoing around the North Atlantic but is not yet complete. Once established and where these limits are not exceeded, the priority should be to ensure that fisheries only exploit surpluses. Changes in egg quality and quantity as a result of reduced condition factor (fatness) of salmon and changes in the incidence of repeat spawners will necessitate a review of the continuing validity of current conservation limits.

Exploitation of stocks that are below their conservation limits should not be permitted or should be limited to a level that will still permit stock recovery. In this regard, the remaining mixed-stock fisheries (MSFs), particularly in coastal waters, pose particular difficulties for management as they cannot target only those stocks that are known to be above their conservation limits. In accordance with NASCO guidance,

Salmon net (top) and rod and line (middle) fisheries and releasing a fish caught during angling (bottom).

where such fisheries operate managers should have a clear policy that takes account of the additional risks and that aims to protect the weakest of the contributing stocks. In most countries, the majority of the catch is now taken in fresh water; the coastal catch having declined markedly. However, in 2010 approximately 30% (419 tonnes) and 6% (10 tonnes) of the catches in the North-East Atlantic and North American Commission areas respectively, were taken in coastal areas, i.e. in MSFs. The new genetic databases together with the development of more rapid, cost-effective genetic assignment methods should assist rational management of these, and other, fisheries in future.

Climate change has been linked to changes in run-timing. To protect vulnerable stocks (or perhaps in some situations to extend fishing opportunities) managers may want to be alert to such changes so as to assess the need to adjust fishing seasons.

Catch and release fishing allows the economic benefits generated by rod and line fisheries to continue to be generated while reducing the level of fishing mortality. In 2010, more than 200,000 salmon were released around the North Atlantic. Catch and release fishing is to be encouraged as an intermediate management strategy between a full retention fishery and fishery closure. Mortality of Atlantic salmon in catch and release fishing is highly variable, and temperature is as an important factor with lower post-release mortalities at temperatures below 17-18°C. Warming of the freshwater environment may have implications for the conservation benefits to be derived from catch and release fishing and this mortality needs to be taken into account particularly when stock levels are low.

The decline in abundance of wild salmon stocks as a result of mortality at sea has given rise to increasing interest in stocking of salmon in order to rebuild stocks. However, the need to stock should be very carefully considered as poorly planned activities could diminish the ability of wild populations to adapt to warmer conditions. That is not to say that stocking does not have a role to play in stock rebuilding or restoration but there is a need to fully consider the risks as well as the benefits.

Bycatches of salmon in pelagic fisheries

There is undoubtedly a bycatch of salmon in fisheries for pelagic species in the Northeast Atlantic but with widely varying estimates. There is also a completely unknown mortality of salmon caused by the gear that would not be detected by screening the catch. Consequently, the scale of the problem is highly uncertain. According to present estimates, it could be insignificant or of a major scale. Such uncertainty is highly undesirable and further efforts should be made to quantify the extent of bycatch. In the light of better estimates, the opportunities for mitigation measures, such as lowering the depth of trawls in pelagic fisheries, may need to be explored with the international and national bodies regulating these fisheries.

Freshwater influences

There have been some notable successes in restoring degraded habitat and improving access in recent years.

Habitat in a salmon river in northern Spain.

However, freshwater environments will be affected by climate change to a greater or lesser extent depending on geography. Maintaining the productive capacity of salmon habitat will require coordinated catchment management planning so as to identify risks to the resource and prioritise and implement measures to address them. Better cooperation between all involved in salmon management and longer-term planning will be valuable. In particular, it may be possible to mitigate some of the anticipated effects of climate change in terms of increased water temperatures and altered flow regimes by planting bankside vegetation to create shade and by changes to land use and land drainage schemes. Minimising contaminants in freshwater may have beneficial effects on marine survival. Removal of barriers to migration should allow unimpeded downstream migration of smolts and upstream migration of adults reducing exposure to predation.

Marine parasites and diseases

While progress has been made in managing impacts of salmon farming, major challenges remain particularly with regard to sea lice and escaped farmed salmon. There is a concern about development of resistance to lice treatments. NASCO and the International Salmon Farmers' Association (ISFA) have agreed that the guiding principle should be that wild salmon populations in areas with salmon farms should be as healthy as those in areas without farms. The following international goals will need to be vigorously pursued:

- 100% of farms to have effective sea lice management such that there is no increase in sea lice loads or lice-induced mortality of wild salmonids attributable to the farms;
- 100% farmed fish to be retained in all production facilities.

Marine predation

Increased predator populations, some linked to warming, may be affecting salmon abundance. The number of predators may be high while post-smolts are migrating over the continental shelf to offshore areas and include fish, marine mammals and birds. Predation in offshore areas may be lower. Ecosystem approaches may offer opportunities to reduce these predator impacts in the future. Predator control and deterrence are controversial issues and, moreover, some of the salmon's main predators are legally protected species. If jurisdictions have or obtain legal powers to regulate or deter predators, and if they chose to use them, there may be benefits to salmon production. Some predators of the salmon are also hosts to parasites that infest salmon.

The restoration of other migratory species, e.g. alewives and blueback herring in the US, may serve both as a valuable source of food for salmon and a buffer from predation (e.g. by predator swamping) in the early stages of migration.

Growth, food and competition at sea

New research has provided insights into the diet of salmon at sea and competition for food and space with other species. However, managers have no influence on the food and growth of salmon at sea, nor on the salmon's competitors for resources. Some of these competitors, e.g. herring and

Grey seals at a haul-out site.

Marine cages at a salmon farm.

mackerel are at high abundance which may deplete the resources available to salmon. If ecosystem management becomes a reality, it may offer fisheries managers the opportunity to fish selectively so as to influence the balance of species in a given sea area. However, for the time being the interactions between pelagic marine species is not sufficiently understood to allow such advanced ecosystem approaches.

Conclusions

It seems clear that the marine environment of the North Atlantic is changing in a way that will cause additional pressures on the wild Atlantic salmon, particularly those in the southern part of the range. We conclude that there are no quick-fix solutions although new information, ideas and tools that can assist managers and support predictive modelling are emerging. It will be challenging for managers as well as the salmon to adapt to these new and uncertain conditions. We support the finding from the 'Salmon Summit' that the rational management approach is to re-double efforts to address factors impacting on productivity to ensure that the 2,500 salmon rivers that flow into the North Atlantic produce the maximum number of healthy wild salmon smolts. That will entail further sacrifices in harvests, more emphasis on habitat protection, restoration and enhancement and further progress in addressing impacts of salmon farming. It will mean more outreach to politicians and the public and to those industries that are impacting salmon habitat. Fortunately, there is a large and diverse community of non-government organizations supporting the species and they can, and should, continue to play a major role in this. There will be a need to plan ahead for these changes and to work cooperatively with those with similar aims. It will not be easy, but the wild salmon has a huge constituency of support in all the countries bordering the North Atlantic and, given the social, economic and political will to take stronger actions, we certainly believe that this iconic species, part of our heritage, can survive. There may be counter-balancing gains through a northern movement of the salmon as it colonises newly accessible habitat in warming northern rivers. However, in the absence of even stronger conservation action for the salmon, there are warnings from the scientists that the species could become extinct in the southern parts of its range in less than 30 years time.

Habitat restoration on the Sedgeunkedunk Stream, a tributary of the Penobscot River, US; before (top) and after (bottom) dam removal.

Key issues

Background

- Over the last forty years, increased mortality at sea, linked to a warming climate, has resulted in a dramatic decline in the abundance of Atlantic salmon.
- Since management options in the ocean are limited the goal should be to maximise the number of healthy wild salmon that go to sea by focusing actions on impact factors in fresh, estuarine and coastal waters.

Salmon fisheries

- The priority should be to establish conservation limits (or other reference points) to ensure that fisheries only exploit surpluses (i.e. where stocks exceed conservation limits); reductions in condition of returning salmon and increases in the incidence of repeat spawners in some areas will need to be taken into consideration in assessing attainment of conservation limits.
- Mixed-stock fisheries (MSFs) pose particular difficulties for management and the weakest of the contributing stocks should be protected.
- Warming of the freshwater environment may have implications for the conservation benefits to be derived from catch and release fishing and this mortality has to be taken into account, particularly when stock levels are low.
- There is increasing interest in stocking of salmon but the risks as well as the benefits need to be considered.

Bycatches of salmon in pelagic fisheries

- There is a bycatch of salmon in fisheries for pelagic species in the Northeast Atlantic but with widely varying estimates. Further efforts should be made to quantify the extent of bycatch and the opportunities for mitigation measures may need to be explored with the bodies regulating these fisheries.

Freshwater influences

- Maintaining the productive capacity of salmon habitat will require coordinated catchment management planning so as to identify risks to the resource and prioritise and implement measures to address them. Better cooperation between all involved in salmon management and longer-term planning will be valuable.
- Planting of bankside vegetation to create shade and changes to land use and land drainage schemes may mitigate some of the expected effects of climate change.

Marine parasites and diseases

- Challenges remain to be addressed in managing impacts of salmon farming. There is a concern about development of resistance to lice treatments.

Marine predation

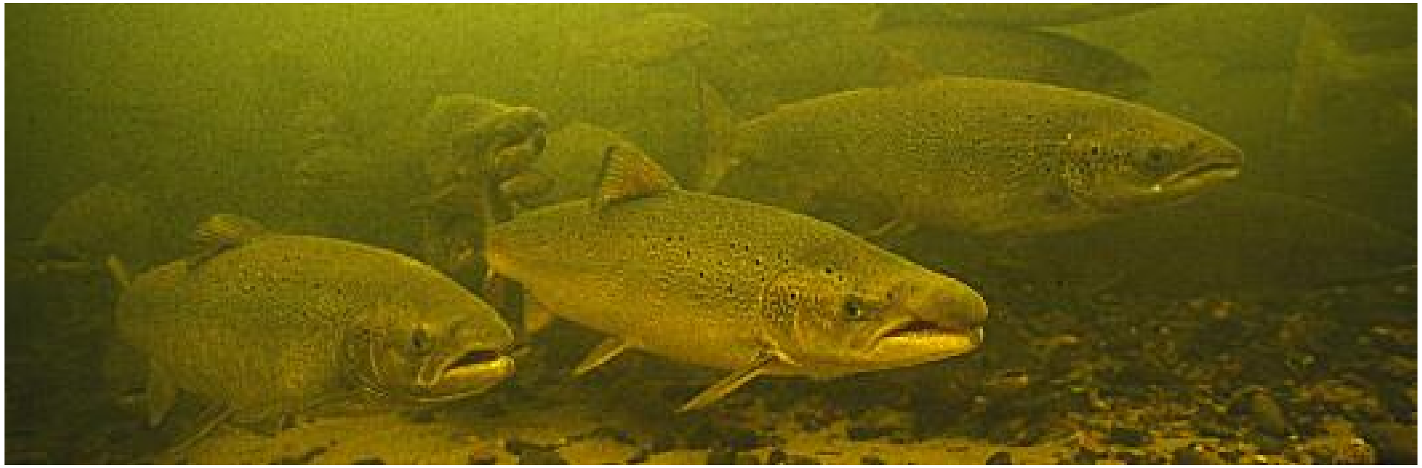
- Predator control is a controversial issue and some of the salmon's main predators are legally protected species. If jurisdictions have or obtain legal powers to regulate predator populations, and if they chose to use them, there may be benefits to salmon conservation.

Growth, food and competition at sea

- Species are moving north affecting the food available to the salmon.
- Managers have no influence on the food and growth of salmon at sea, nor on the salmon's competitors for resources e.g. herring and mackerel. However, if ecosystem management becomes a reality it may offer the opportunity to fisheries managers to fish selectively so as to influence the balance of species in a given sea area.

The future

- There are no quick-fix solutions although new information, ideas and tools that can assist managers and support predictive modelling are emerging. There will be a need to plan ahead for these changes and to work cooperatively with those with similar aims.
- There will need to be more outreach to politicians and the public and to those industries that are impacting the salmon and its habitat. The large and diverse community of non-government organizations supporting the species can play a major role.
- There may be counter-balancing gains through a northern movement of the salmon as it colonises newly accessible habitat in warming northern rivers. However, in the absence of even stronger conservation action for the salmon, there are warnings from the scientists that the species could become extinct in southern parts of its range in less than 30 years time.



Acknowledgements

We would like to acknowledge the contributions of the many individuals and organizations involved in the SALSEA Programme and the 'Salmon Summit'. NASCO's International Atlantic Salmon Research Board (IASRB) developed the SALSEA Programme and provided initial funding for this ambitious and innovative initiative, probably the largest international cooperative research programme ever conducted on Atlantic salmon. The SALSEA-Merge project involved a consortium of twenty organizations, from both the public and private sectors, and received generous funding from the EU Seventh Framework Programme (FP7). Contributions in support of this project were made to NASCO's IASRB by the Total Foundation and the Atlantic Salmon Trust and this exceptional support is very gratefully acknowledged. The Irish, Norwegian and Faroese governments contributed through the provision of research vessel time and personnel and other governments contributed personnel. The SALSEA North America marine surveys involved Canadian and US government funding and the tracking studies were funded by the Atlantic Salmon Federation. The US government made funds available to the IASRB for the SALSEA West Greenland project that involved scientists from Canada, Greenland, Ireland, the UK and the US.

We would like to acknowledge the expertise and dedication of the many scientists from different disciplines who participated in the programme. We are privileged to be charged with synthesising the work, completed to date, into advice for managers and hope that we have been able to do it justice. We thank those who have made such a significant contribution to understanding the ocean life of the salmon. We are confident that much more valuable information will emerge from this enormous research effort.

Photographs courtesy of Dave Reddin, Niall Ó Maoiléidigh, Lars Petter Hansen, Sergey Prusov, Fred Whoriskey, Iain McLaren, Jan Arge Jacobsen, Gilbert van Ryckevorsel, Kjell Arne Mork, Jens Christian Holst, Chris Todd, Ross Jones, Paul Music, Peter Hutchinson, Oystein Aas, Rory Saunders, Scottish Salmon Producers' Organization and the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS). The images on page 9 are reproduced from a paper by Mork et al. (2012) from the 'Salmon Summit' issue of the ICES Journal of Marine Science (volume 69). We are grateful to the General Secretary of ICES for permission to use the data on pre-fishery abundance in the graphs on page 1.