# BENCHMARK WORKSHOP ON ATLANTIC SALMON IN THE NORTH ATLANTIC (WKBSALMON)

*March 2024: Report updated with additional working document (WD10-Retrospective-patterns-LCM-2024) and explanatory paragraph in Executive Summary*

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# i Executive summary


WKBSalmon reviewed the implementation of a Life Cycle Model (LCM) for wild anadromous Atlantic salmon (*Salmo salar* L.) covering their natal north Atlantic range. The LCM is a time iterative, Bayesian hierarchical model incorporating salmon records of fifteen countries at 25 stock-units. It tracks salmon of two explicit sea-age streams, namely, one-sea-winter (1SW) and multi-sea-winter (MSW), stock unit specific smolt ages, numbers of salmon returning to stock-units, proportions maturing, survival at sea by month and stock unit specific post-smolt survival rates and proportion maturing at 1SW. Mixed-stock catches at West Greenland and Faroes, as well as those in North America, are designated to stock-units based on observed historic tag data, genetic identification and assumed harvest distributions.

The LCM will replace three Pre-Fisheries Abundance (PFA) forecast models, aligned to three management units, one eastern North America and two Northeast Atlantic European complexes of stock-units. The LCM enables a more comprehensive and consistent approach, account-ing for migration and maturation of salmon by stock-unit and a hierarchical (over stock-units) modelling of post-smolt survival and proportion maturing in the first year at sea.

The LCM uses outputs from two "Run Reconstruction" models, one for each of eastern North America and Northeast Atlantic origin salmon. These processes catch data and exploitation rates and / or returns at stock-unit spatial scales to estimate returning numbers and catches of salmon by sea-age group. The LCM model uses a similar sea-age group structure for all stock-units resulting in a harmonized life cycle for Atlantic salmon from the North Atlantic.

The LCM forecasts estimates of returning salmon by stock-unit based on the post-smolt survival and proportion maturing parameters, forecast forward as a random-walk, from the most recent observations and accounting for "banked" maturing and non-maturing salmon. Fore-cast returns to stock-units may be compared to Conservation Limit (CL) reference points and "Spawner Escapement Reserves" (SERs – reference points prior to any marine fishing activities) at national and international levels to quantify the risk to the salmon stocks under different mixed-fisheries catch levels.

The LCM was found to provide estimates of stock status and forecasts in line with perceptions and previously used modelling frameworks and to be robust to a range of settings and uncertainties. Subsequent to the meeting, retrospective patterns of the primary model variables (Total PFA, Maturing PFA, Non-maturing PFA, Post-smolt survival and Probability of maturing as 1SW) for all stock units were investigated using Mohn's rho and time series graphing using the full time series and five "peels" each produced by running the assessment model with a further proceeding year's data removed. These also showed the model to be stable, with retrospective patterns with acceptable bounds (ICES, WKFORBIAS; 2020). This work is added to the report as a standalone document listed in Annex 2 (Rivot and Dubost, 2024).

# ii Expert group information

| | |
|---|---|
| **Expert group name** | Benchmark Workshop on Atlantic Salmon (*Salmo salar*) in the North Atlantic (WKBSALMON) |
| **Expert group cycle** | Annual |
| **Year cycle started** | 2023 |
| **Reporting year in cycle** | 1/1 |
| **Chair(s)** | Jonathan White (Ireland) |
| | Tommi Perälä (Finland) |
| **Meeting venue(s) and dates** | 15–17 November 2022 |
| | 20–23 June 2023 (online) |
| | 23–27 October 2023 (ICES HQ, Copenhagen, Denmark) |

# 1 Introduction

WKBSalmon was organized with the primary purpose of reviewing, checking and consolidating a Bayesian state-space Life Cycle Model (LCM) representation of wild anadromous Atlantic salmon (*Salmo salar* L.) stocks covering their geographic range across the North Atlantic. This model has been developed through activities of members of the ICES Working Group on North Atlantic Salmon (WGNAS) with its first notable developments in the form of a single country life cycle example model founded around collaboration of the EU FP7 project ECOKNOWS (2010-2014).

In forecasting stock status, the WGNAS has to date followed a series of processes. Regional data compilation, for groups of countries / stock-units, is standardised and submitted to the Working Group. Data are then processed through American (North American Commission; NAC) and northern and southern European (respectively N-NEAC and S-NEAC: North East Atlantic Commission) “Run Reconstructions” (RR), which provide standardised data of returns, spawners, lagged eggs or lagged spawners for two sea-age classes, namely one-sea-winter (1SW) and multi-sea-winter (MSW). These were then subsequently used in NAC, N-NEAC and S-NEAC “Pre-Fisheries Abundance” (PFA) forecast models to develop ICES advice on fishing opportunities, last implemented in ICES (2021). Implementation of the LCM will move the hindcasting and forecasting elements of the assessments away from three independent PFA models to a single unified model (Figure 1.1).

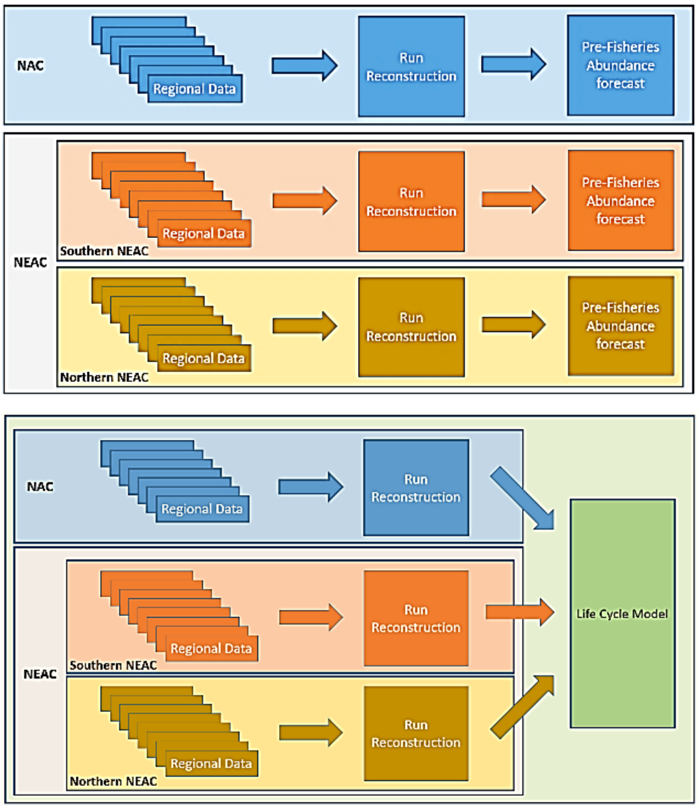


**Figure 1.1. Representation of North Atlantic Salmon assessment framework with (top) independent Pre-Fisheries Forecast models and (bottom) single unified North Atlantic Life Cycle Model.**

The LCM replaces the three PFA models with a single North Atlantic-wide hindcasting (based on historical observations) and forecasting approach. This model tracks salmon across the three North Atlantic Salmon Conservation Organization (NASCO) commissions – NAC, NEAC and

West Greenland Commission (WGC). It includes mixing of stocks at West Greenland and the Faroes, the two mixed stock fishing areas considered by NASCO. It considers two sea-age class groups, 1SW and MSW. The MSW age class is strictly calculated as fish spending two years at sea (2SW), however it may be considered a "plus-group", concordantly combining salmon of two, three and older first-time spawning age groups and repeat spawners. Predominantly, numbers relate to 2SW salmon but will be referred to as MSW.

Outputs of the LCM are in line with the previously employed Pre-Fisheries Abundance (PFA) forecast models, providing for NEAC and NAC, by country and assessment units, assessment time-series and 5 years forecasts (the current and previous years – necessary to forecast owing to data requirements in back calculations of 2SW salmon – and forward three years) of total PFA, PFA maturing (1SW), PFA non-maturing (MSW), Productivity (post-smolt survival), Proportion maturing as 1SW, Returns of 1SW, Returns of MSW and eggs in returns/spawners of 1SW, MSW and all sea-age groups.

Advantages of the LCM are that it provides a single, unified assessment framework, data-framework and workflow and links the productivity and maturation processes at sea hierarchically among all stock-units. In addition, it provides a more realistic representation of the life-cycles and interactions of salmon stocks and fisheries that share a common albeit large marine environment and improved stock-unit biology (freshwater survival rates, biological characteristics).

During the benchmark process data were reviewed and updates were incorporated as appropriate.

# 2 Terms of Reference

## 2.1 WKBSALMON – Benchmark Workshop on Atlantic Salmon (*Salmo salar*) in the North Atlantic

2022/2/FRSG47 A Benchmark Workshop on Atlantic salmon (*Salmo salar*) in the North Atlantic, chaired by External Chair Tommi Perälä (FI) and ICES Chair Jonathan White (IE) and attended by invited external experts Chris Legault (USA) and Grant Hanson (USA). The benchmark will be established as a series of workshops that will work to:

1. scope the work and create a workplan for the benchmark;
    a) update the BWKSalmon ToRs with chairs and reviewer names, workshop dates for ToRs 2 and 3;
    b) complete Table 1
2. compile data and evaluate quality;
3. develop the assessment and associated tools to provide advice;
4. document all methods and data used and agreed upon by the benchmark in the stock annex; and
5. develop recommendations for future improvements of the assessment methodology and data collection.

Re: ToR 1. BWKSalmon will meet at ICES HQ 15–17 November 2022 for a scoping workshop. This scoping workshop will work to identify not only the scope of work for the benchmark, but it will also lay out the work plan and schedule for subsequent ICES workshops that are part of this benchmark and identify relevant participants and external experts to contribute to this work. Dennis Ensing (UK) and Etienne Rivot (France) will chair this meeting.

Re: ToR 2. BWKSalmon will conduct a data evaluation workshop, which may include the publication of an ICES data call[1] to support this work. The workshop will be held 20th -23rd June 2023 online. This workshop will consider the quality of input data proposed for use in the assessment, make a proposal to the benchmark on the use and treatment of data for each assessment, including discards, surveys, life history, fishery-dependent, recreational, etc. Stakeholders are invited to contribute data (including data from non-traditional sources) and to contribute to data preparation and evaluation of data quality.

Re: ToR 3. A methods workshop will be held 23–27 October 2023 at ICES HQ in Copenhagen, with hybrid meeting access for all participants. In preparation for the methods workshop, working documents and input data should be delivered by the participants following the DEWK (data evaluation workshop) and at least 14 days in advance of the methods workshop. The methods workshop should agree to and thoroughly document the most appropriate method for conducting the stock assessment, the method and values for fisheries and biomass reference points that follow the best available science and are in line with ICES guidelines (see the latest Technical guidance on reference points).

As part of the methods workshop, knowledge about environmental drivers, including multispecies interactions and ecosystem impacts should be integrated in the methodology. A full suite of diagnostics (regarding data, retrospective behaviour, model fit, predictive power

[1] ICES (2023). WKBSALMON-2-2023: Data submission for ICES Benchmark Workshop on North Atlantic salmon stocks.. Data Calls. Report. https://doi.org/10.17895/ices.pub.23098502.v1

etc.) should be examined as a whole to evaluate the appropriateness of any model developed and proposed for use in generating advice.

Please note the work presented in ICES meetings WGNAS, WKSalModel, WKSalmon1 and WKSalmon2 that was done in preparation of this benchmark, originally named WKSalmon3; the ICES data call[2] issued from work done in WKSalmon2 will thus be taken up as part of this benchmark.

Re: ToR 4. The method for conducting the short-term forecast and determination of fishing mortality and biomass reference points should also be included as part of this work. This can be done through the stock annex and in the Transparent Assessment Framework (TAF).

If additional time is needed to agree to reference points and the short-term forecast, the benchmark can agree to additional meeting days.

If no analytical assessment method can be agreed, then an alternative method (the former method, or following the ICES data-limited stock approach see WKLIFE X (https://doi.org/10.17895/ices.pub.5985) should be put forward by the benchmark.

The Benchmark Workshop will report for the attention of ACOM by 17 November 2023.

**Table 1. The benchmark scope. To be completed by the WKBsalmon scoping meeting. Identify the people/institutes responsible for assessments and data as well as the objective of the benchmark for Atlantic salmon in each commission area. If the benchmark will not conduct work for Atlantic salmon in a commission area, it should be stated here.**

| Salmon Assessment Areas | Stock leaders* | ICES stock category and assessment method |
|---|---|---|
| Atlantic salmon (*Salmo salar*) from North America sal.nac.all | **Assessment**: Institut Agro DECOD /DFO Science<br>**Data**: DFO Science/ NOAA<br>Other: | Category 1<br>Analytical model, run-reconstruction models and Bayesian forecasts, taking into account uncertainties in the data.<br>Benchmark objective to transition to LCM |
| Atlantic salmon (*Salmo salar*) in Northeast Atlantic and Arctic Ocean sal.neac.all | **Assessment**: Institut Agro DECOD/ NIAN/ Marine Institute/ Cefas<br>**Data**: NIAN/ Marine Institute/ Cefas/ DFO Science/ NOAA<br>Other: | Category 1<br>Analytical model, run-reconstruction models and Bayesian forecasts, taking into account uncertainties in data<br>Benchmark objective to transition to LCM |
| Atlantic salmon (*Salmo salar*) in Subarea 14 and NAFO division 1 (east and west of Greenland) sal.wgc.all | **Assessment**: Institut Agro DECOD/ DFO/ NOAA Marine Institute/ Cefas<br>NIAN/ DFO/ Marine Institute/ Cefas<br>**Data**: NIAN/ Marine Institute/ Cefas/ DFO Science/ NOAA<br>Other: | Category 1<br>Analytical model, run reconstruction models and Bayesian forecasts, taking into account uncertainties in the data.<br>Benchmark objective to transition to LCM |

* Note these classifications do not align with the assessment approach. Both “Assessment” and “Data” have been aligned to the primary organisations compiling data and running assessment elements to date and do not constitute a definitive list. Owing to the crossover of data and assessment, the application of RRs and the LCM is very much a team effort. Responsibilities will be detailed in the WGNAS 2024/2025.

[2] ICES. 2023. Data call - WKSALMON-2023 Data submission for selected stocks in support of WKSalmon3, WKBSalmon and WGNAS. https://doi.org/10.17895/ices.pub.22274884

# 3 North Atlantic salmon: stocks, countries, and management units

Atlantic salmon (*Salmo salar* L.) is an obligatory freshwater spawner. Anadromous (populations with life stages that migrate to the marine environment for part of their life cycle) Atlantic salmon spawn and occupy more than 2400 rivers in countries bordering the North Atlantic. Juvenile salmon may reside in rivers for 1 to as many as 8 years before migrating to the ocean as smolts to complete their growth and maturation process. Smolt ages increase with latitude on both sides of the North Atlantic (Metcalfe and Thorpe 1990). Many salmon from the Northeast Atlantic migrate to feeding grounds off the Faroes and the Norwegian Sea, overwinter and either return as 1SW salmon or migrate to feeding grounds around West Greenland or the Irminger and Barents Sea returning after 2, 3, 4 and even up to 6 winters at sea. As with smolt ages, older sea-ages and repeat spawners (both consecutive and alternate repeat spawner strategies) are generally more common in northern rivers of origin. Salmon from the Northwest Atlantic undergo feeding migrations to the Labrador Sea, West Greenland and in some cases into the Northeast Atlantic into areas proximate to the Faroe Islands sea-age

Countries, management and assessment units are aligned with North America (NAC), southern Europe (S-NEAC) and northern Europe (N-NEAC) stock complexes used by ICES and NASCO and (Figure 3.1).

The 25 stock-units are grouped within three large stock complexes:

- 6 stock-units for the North American continental stock group (NAC): Labrador, Newfoundland, Quebec, Gulf, Scotia-Fundy, USA;
- 8 stock-units for the Southern European continental stock group (S-NEAC): France, UK England and Wales, Ireland, UK Northern Ireland - FO, UK Northern Ireland - FB, UK Scotland East, UK Scotland West, Iceland South-West;
- 11 stock-units for the Northern European continental stock group (N-NEAC): Iceland North-East, Sweden, Norway South-East, Norway South-West, Norway Middle, Norway North, Finland, Russia Kola Barents, Russia Kola White Sea, Russia Arkhangelsk Karelia and Russia River Pechora.

The N-NEAC is further separated in two sub-complexes to consider differences in the migration routes (which in particular results in different availability of the fishes at the Faroes fisheries):

- The southern part of the N-NEAC (NNEAC-south), that comprises Iceland North-East, Sweden, Norway South-East, Norway South-West and Norway Middle.
- The northern part of the N-NEAC (NNEAC-north), that comprises Norway North, Finland, Russia Kola Barents, Russia Kola White Sea, Russia Arkhangelsk Karelia and Russia River Pechora.

Note that Netherland, Germany, Spain and Portugal (all being part of the Southern European complex (S-NEAC) and Denmark (possibly S-NEAC but to be determined) are not considered in the current version of the assessment model because no complete series of data are currently available. Salmon stocks from the Inner Bay of Fundy (Canada) are also not considered within the current version of the assessment as these populations are assumed to not migrate to distant waters.

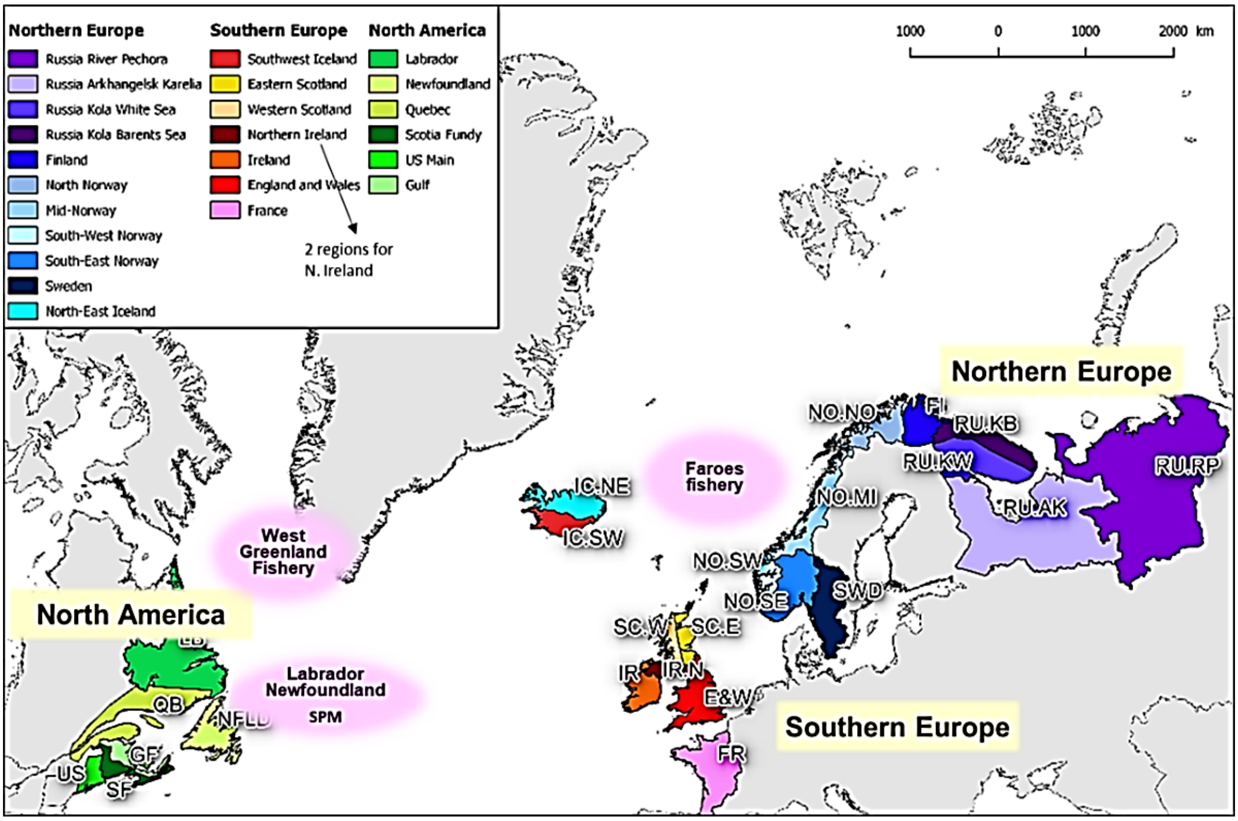


**Figure 3.1. The 25 stock-units considered in North Atlantic. Stock-units of North America: NFLD=Newfoundland, GF=Gulf, SF=Scotia-Fundy, US=USA, QB=Quebec and LB=Labrador; Stock-units of Southern Europe (S-NEAC): IR=Ireland, E&W=England&Wales, FR=France, E.SC=Eastern Scotland, W.SC=Western Scotland, N.IR=Northern Ireland FO (Foyle bassin) and FB (DAERA (Department of Agriculture, Environment and Rural Affairs) region; note the split between FO and FB is not represented on the map), IC.SW=South-West Iceland; Stocks units in Northern Europe (N-NEAC): FI=Finland, IC.NE=North-East Iceland, NO.MI=Middle Norway, NO.NO=North Norway, NO.SE=South-East Norway, NO.SW=South-West Norway, RU.AK=Russia Arkhangelsk Karelia, RU.KB=Russia Kola Barents Sea, RU.KW=Russia Kola White Sea, RU.RP=Russia River Pechora, SWD=Sweden. Germany, The Netherlands, Denmark, Spain and Portugal are not included in the model. Pink ellipses indicate the main fisheries at sea operating on mixed stocks: Faroes, West Greenland, Labrador and Newfoundland (LAB/NFLD) and Saint Pierre and Miquelon (SPM).**

# 4 Data review

Atlantic salmon are native to the temperate and subarctic regions of the North Atlantic Ocean and there are over 2000 rivers draining into the North Atlantic that support the fish, about 1500 of which discharge into the Northeast Atlantic and 900 in the Northwest Atlantic. In this area, salmon distribution extends from northern Portugal (41.87ºN), to Iceland, to north eastern Russia (71.06ºN, Norway), while in the Northwest Atlantic, the species ranges from northeastern USA 41.29ºN) to northern Canada (Ungava Bay; 58.78ºN). Atlantic salmon from the North Atlantic are distinct from salmon populations of rivers of the Baltic Sea, are subject to different fisheries and are managed by different Regional Fisheries Management Organisations (RFMO); the North Atlantic salmon are of interest to the North Atlantic Salmon Conservation Organisation (NASCO).

Large rivers and their tributaries can support several genetically distinct populations; however, it is not always possible to demarcate clear population boundaries within a river and managing stocks and fisheries at this level of detail would be very complex. Thus, while there is a need to protect the sustainability of these units, the primary management unit (e.g. for reporting catch statistics and regulating fishing) is generally taken to be the river stock, comprising all fish originating from eggs laid within the river.

Atlantic salmon would, ideally, be assessed and managed on the basis of river-specific stock-units. In reality, a small proportion (generally < 25%) of the rivers with salmon populations in the North Atlantic are so assessed and consequently, stock status for NASCO is assessed at broader regional, national and subcontinental scales.

Data for assessment of North Atlantic Salmon by the WGNAS are provided by member countries. Data are provided aggregated to the level of stock-units (Figure 3.1) within countries by the national competent authorities.

The opportunity was provided through the Benchmark before the June 2023 meeting for National laboratories to review and update values prior to model implementation in 2023. This process also provided the opportunity to consider adding other country/ stock-units to the assessment.

## 4.1 North East Atlantic Commission (NEAC) Data

Data from the North East Atlantic Commission are aggregated to 19 stock-units across the N-NEAC and S-NEAC stock complexes (Table 4.1). A Run Reconstruction model is used to derive numbers of returns to each stock unit which, together with catches for each stock unit, comprise the main NEAC inputs to the LCM.

The RR model was originally used to provide inputs into the PFA forecasting model and is detailed in Potter *et al*. (2004). In addition to returns, the model derives PFA estimates and spawner abundance estimates, which are not required by the LCM. For stock-units that do not have nationally derived conservation limits (CLs), the RR model derives CLs through a 'pseudo' stock-recruitment relationship (Potter *et al.* 1998). The inputs to the RR model comprise annual time-series data and multi-annual data.

### 4.1.1 Annual time-series data

For the majority of stock-units the annual data include reported catch numbers by sea-age, together with estimates of unreported catch and exploitation rates by seas age each with associated uncertainty. For these stock-units the number of returns is then derived by raising the catches (after accounting for unreporting) by the exploitation rate for each age class.

For stock-units where alternative derivations of return estimates are more appropriate, different data are provided:

- For UK (Scotland), returns are derived nationally and provided directly as inputs to the RR model.
- From 2021 onwards, UK (England) returns are modelled from rod catch and release numbers instead of (total) reported catch.
- From 2000 onwards, UK (Northern Ireland – DAERA) returns are derived from catches and (scaled) counts from the rivers Bush and Bann.
- For Russia, annual time series for all stock-units were not updated with data for the years 2021 and 2022. ICES agreed an approach for the 2023 assessment to account for this deficiency by constructing catch estimates using alternative data sources (ICES, 2023). Additionally, an adjustment is made to the returns estimates to account for the additional uncertainty in the catches. Alternative approaches for accounting for this deficiency were discussed by WKBSalmon but were ultimately rejected in favour of the established method used by the ICES Working Group on North Atlantic Salmon (WGNAS) in 2023.

The N-NEAC forecast time series runs comprehensively from 1983 to 2022 (Table 4.1). While data for many regions are available from 1971, Norwegian data begin in 1983 and with six smolt ages, plus a two year sea-age, giving a first reporting year of 1991. For the S-NEAC stock-units (Table 4.1) time series run from 1971 to present. With the oldest smolt age being five years, plus two year sea-ages, the first reporting year is 1978. Further details of the Run-Reconstruction model and its inputs are provided in the Stock Annex.

**Table 4.1. Time series ranges of available data for Atlantic salmon by stock unit for the Northern European (N-NEAC) and Southern European (S-NEAC) complexes.**

| Continental Stock Complex | Region | From | To |
|---|---|---|---|
| Northern Europe (N-NEAC) | Finland | 1971 | Present |
| | Iceland North-east | 1971 | Present |
| | Norway - North | 1983 | Present |
| | Norway - Southeast | 1983 | Present |
| | Norway Mid | 1983 | Present |
| | Norway - Southwest | 1983 | Present |
| | Russia - Archangel -Karelia | 1971 | Present |
| | Russia - Kola Barent | 1971 | Present |
| | Russia - Kola-White | 1971 | Present |
| | Russia - Pechora River | 1971 | Present |
| | Sweden | 1971 | Present |
| Southern Europe (S-NEAC) | England & Wales | 1971 | Present |
| | France | 1971 | Present |
| | Iceland South-west | 1971 | Present |
| | Ireland | 1971 | Present |
| | Northern Ireland – DAERA* | 1971 | Present |
| | Northern Ireland - Foyle | 1971 | Present |
| | Scotland - East | 1971 | Present |
| | Scotland - West | 1971 | Present |

* DAERA (Department of Agriculture, Environment and Rural Affairs) region

### 4.1.2 Biological characteristics

In addition to time series of catches, exploitation rates and counts of fish, a set of biological characteristics are required as input to the lifecycle model. For most stock-units, fixed values are used. The exceptions are UK (England & Wales) and UK (Scotland), which provide time-series of fecundity (number of eggs per female) and proportion of females.

**Table 4.2. Biological characteristics and average annual number of spawners for each stock unit. Fecundity is the expected number of eggs produced per female. Return month is the mid-month of return (since Jan. 1). Sex ratio is proportion of females. Spawners are given in number of fish and are included because they are used to convert between CLs in term of eggs and fish and to split total CL of eggs into a 1SW and a MSW component (Table 4.3). Biological characteristics are the averages for the last 10 years (when provided as time-series).**

| Stock unit | Return month 1SW | Return month MSW | Sex ratio 1SW | Sex ratio MSW | Fecundity 1SW | Fecundity MSW | Spawners 1SW | Spawners MSW |
|---|---|---|---|---|---|---|---|---|
| **S-NEAC:** | | | | | | | | |
| France | 8.5 | 8.5 | 0.450 | 0.800 | 3 485 | 5 569 | 11 922 | 5 168 |
| UK(E & W) | 8.0 | 6.0 | 0.458 | 0.702 | 4 080 | 7 043 | 35 657 | 90 301 |
| Ireland | 8.0 | 5.0 | 0.600 | 0.850 | 3 400 | 7 000 | 168 899 | 18 405 |
| UK(N. Ireland) FO | 6.5 | 5.0 | 0.570 | 0.600 | 3 459 | 6 781 | 21 558 | 2 336 |
| UK(N. Ireland) FB | 7.0 | 5.5 | 0.570 | 0.600 | 3 459 | 6 781 | 13 953 | 1 950 |
| UK(Scotland) EA | 8.0 | 5.0 | 0.495 | 0.714 | 3 274 | 6 177 | 168 936 | 172 934 |
| UK(Scotland) WE | 8.0 | 7.0 | 0.495 | 0.714 | 3 282 | 6 179 | 35 337 | 12 870 |
| Iceland SW | 7.0 | 6.0 | 0.420 | 0.570 | 5 954 | 10 787 | 21 118 | 2 765 |
| **N-NEAC:** | | | | | | | | |
| Iceland NE | 7.0 | 6.0 | 0.330 | 0.630 | 5 982 | 11 666 | 9 529 | 3 734 |
| Sweden | 8.3 | 7.5 | 0.310 | 0.610 | 3 113 | 7 625 | 3 786 | 5 292 |
| Norway SE | 8.0 | 5.0 | 0.362 | 0.682 | 2 449 | 7 250 | 30 545 | 43 300 |
| Norway SW | 8.0 | 5.0 | 0.362 | 0.682 | 2 449 | 7 250 | 5 712 | 14 925 |
| Norway MI | 8.0 | 5.0 | 0.464 | 0.673 | 2 262 | 7 619 | 49 928 | 52 423 |
| Norway NO | 8.0 | 5.0 | 0.175 | 0.710 | 2 571 | 9 399 | 20 932 | 28 877 |
| Finland | 6.0 | 6.5 | 0.120 | 0.770 | 5 000 | 13 000 | 12 646 | 8 912 |
| Russia AK | 7.5 | 8.0 | 0.100 | 0.800 | 4 500 | 12 000 | 3 515 | 5 021 |
| Russia KW | 8.5 | 7.5 | 0.600 | 0.400 | 4 500 | 10 500 | 55 091 | 7 684 |
| Russia KB | 7.0 | 6.5 | 0.100 | 0.800 | 3 500 | 12 500 | 6 943 | 5 312 |
| Russia RP | 8.0 | 8.0 | 0.100 | 0.700 | 4 500 | 15 000 | 1 439 | 10 793 |

### 4.1.3 Updates to the NEAC data

The following data was updated for the benchmark. UK (England & Wales) updated proportion of females and eggs per female from static values to time series (1971 – present). France updated their static values of proportion of females and eggs per female. Sweden updated all their static values, which includes proportion of females, eggs per female, smolt age distribution and mid-months of returns.

### 4.1.4 Conservation Limits for NEAC

River-specific Conservation Limits (CLs) have been derived for salmon stocks in most countries in the NEAC area (France, Ireland, UK – England and Wales, UK – Northern Ireland, UK – Scotland, Finland, Norway and Sweden) and these are used in national assessments. In these cases, CL estimates for individual rivers are summed to provide estimates at the national level for these countries. For Ireland, national CLs are provided in numbers of 1SW and MSW spawners, while for the other aforementioned countries, CLs are provided in total number of eggs for each stock unit. During the benchmark, France, UK – England and Wales and Sweden have updated their CLs and biological characteristics.

River-specific CLs have also been derived for several rivers in Russia and Iceland, but these are not yet used in national assessments. An interim approach has been developed for countries that do not use river-specific CLs in their national assessment. This approach is based on the establishment of pseudo–stock–recruitment relationships for national salmon stocks; further details are provided in the Stock Annex (Annex 5).

The updated CLs in their various forms (number of eggs or fish) are presented in **Table 4.3**. To convert between CLs in number of fish and number of eggs for age group $x$ (1SW or MSW) the following relationship has been used:

$$\mathrm{CL_{eggs}}(x) = \mathrm{CL_{fish}}(x) \times \mathrm{SexRatio}(x) \times \mathrm{Fecundity}(x),$$

where $\mathrm{SexRatio}(x)$ is the proportion female for age group $x$ and $\mathrm{Fecundity}(x)$ is the average number of eggs per female for age group $x$.

To split the total CL in number of eggs ($\mathrm{CL_{total}}$) into the sea-age groups:

$$\mathrm{CL_{eggs}}(x) = \mathrm{CL_{total}} \frac{\mathrm{Eggs}(x)}{\sum_x \mathrm{Eggs}(x)},$$

where $\mathrm{Eggs}(x)$ is the average annual number of eggs produced by age group $x$ in the last 10 years given by:

$$\mathrm{Eggs}(x) = \mathrm{Spawners}(x) \times \mathrm{SexRatio}(x) \times \mathrm{Fecundity}(x),$$

where $\mathrm{Spawners}(x)$ is the average number of annual spawners in the last 10 years. The biological characteristics used for these translations are given in Table 4.2. CL estimates for all individual stock-units can be summed to provide estimates at the country level and for the Northern and Southern NEAC stock complexes. Note that for UK – England and Wales, $\mathrm{CL_{total}}$ was split into its age components nationally and directly provided to the working group and Ireland provided their CLs in numbers of 1SW and MSW fish. For all other stock-units, the CLs are provided as $\mathrm{CL_{total}}$.

These data are also used to estimate the Spawner Escapement Reserves (SERs; the CL increased to take account of natural mortality between the recruitment date of 1st January in the first sea winter and return to home waters).

$$\mathrm{SER}(x) = \mathrm{CL_{fish}}(x) \times e^{m \times t(x)},$$

where *e* denotes Euler's number, *m* = 0.03 is monthly marine mortality and *t*(x) the number of months between Jan. 1 of the first winter at sea and returns to rivers for sea-age x. SERs are estimated for maturing (1SW) and non-maturing (MSW) salmon for each stock unit (Table 4.3).

**Table 4.3. Conservation limits for each stock unit in numbers of eggs and fish and the spawning escapement reserve (SER) in number of maturing (mat.) and non-maturing (non-mat.) 1SW fish.**

| Stock unit | CL eggs total | CL eggs 1SW | CL eggs MSW | CL fish 1SW | CL fish MSW | SER mat. | SER non-mat. |
|---|---|---|---|---|---|---|---|
| **S-NEAC:** | | | | | | | |
| France | 77 676 434 | 34 809 471 | 42 866 963 | 22 196 | 9 622 | 28 644 | 17 796 |
| UK(E & W) | 262 754 562 | 104 570 366 | 158 184 196 | 55 961 | 31 994 | 71 140 | 54 871 |
| Ireland | 710 711 690 | 431 400 840 | 279 310 850 | 211 471 | 46 943 | 268 832 | 78 174 |
| UK(N. Ireland) FO | 665 00 000 | 54 347 548 | 12 152 452 | 27 565 | 2 987 | 33 500 | 4 974 |
| UK(N. Ireland) FB | 273 00 000 | 21 189 166 | 6 110 834 | 10 747 | 1 502 | 13 258 | 2 539 |
| UK(Scotland) EA | 426 323 670 | 112 611 215 | 313 712 455 | 69 486 | 71 131 | 88 334 | 118 454 |
| UK(Scotland) WE | 13 4749 652 | 67 745 481 | 67 004 171 | 41 700 | 15 187 | 53 011 | 26 855 |
| Iceland SW | 51 606 484 | 39 038 779 | 12 567 705 | 15 611 | 2 044 | 19 259 | 3 508 |
| **N-NEAC:** | | | | | | | |
| Iceland NE | 23 473 523 | 9 546 304 | 13 927 219 | 4 836 | 1 895 | 5 966 | 3 252 |
| Sweden | 14 085 976 | 1 820 594 | 12 265 382 | 1 887 | 2 637 | 2 420 | 4 733 |
| Norway SE | 85 098 198 | 9 554 841 | 75 543 357 | 10 778 | 15 278 | 13 701 | 25 442 |
| Norway SW | 35 828 123 | 2 300 646 | 33 527 477 | 2 595 | 6 781 | 3 299 | 11 292 |
| Norway MI | 230 635 712 | 37 626 794 | 193 008 918 | 35 850 | 37 641 | 45 574 | 62 682 |
| Norway NO | 92 459 310 | 4 308 112 | 88 151 198 | 9 575 | 13 210 | 12 172 | 21 997 |
| Finland | 104 274 286 | 8 173 744 | 96 100 542 | 13 623 | 9 600 | 16 310 | 16 723 |
| Russia AK | 59 969 694 | 1 905 397 | 58 064 297 | 4 234 | 6 048 | 5 303 | 11 020 |
| Russia KW | 158 641 870 | 130 358 477 | 28 283 393 | 48 281 | 6 734 | 62 305 | 12 087 |
| Russia KB | 81 292 441 | 3 556 157 | 77 736 284 | 10 160 | 7 774 | 12 535 | 13 542 |
| Russia RP | 92 985 618 | 528 303 | 92 457 315 | 1 174 | 8 805 | 1 492 | 16 044 |

## 4.2 North American Commission Data

In the Northwest Atlantic anadromous Atlantic salmon (*Salmo salar* L.) ranges from northeastern USA (State of Connecticut; 41.29ºN, 72.34ºW) to northern Canada (Ungava Bay; 58.78ºN 70.25ºW). There are 900 anadromous Atlantic Salmon rivers in the northwest Atlantic area, 855 rivers in eastern Canada and 45 anadromous Atlantic Salmon rivers in the USA (NASCO rivers database).

### 4.2.1 Stock units for North American Commission Area (NAC)

There are no changes in the stock-units for NAC from those originally defined for the ICES PFA forecast and modelling approach.

The ICES run reconstruction, PFA forecast model and the Life Cycle Model aggregate individual river abundances into six stock-units for North America: the USA and the five main provincial / jurisdictional regions in eastern Canada comprising Labrador, Newfoundland, Quebec, Gulf and Scotia-Fundy (Figure 4.1). The stock-units reflect the jurisdictional boundaries of the Fisheries and Oceans Canada, the province of Quebec and the USA. For Canada, the stock-units are aggregates of management areas, termed Salmon Fishing Area (SFA) and Quebec management zones (Q) (Figure 4.1; Table 4.4). The stock-units correspond in large part to the geographic structure of sea-age and life history characteristics of anadromous salmon in eastern Canada (Porter *et al.*, 1986; O'Connell *et al.*, 2006). The compilations of data on stocks within each jurisdiction are of importance to regional / national managers.

Recently, Bradbury *et al*. (2021; and earlier work) reported on the identification of genetically discrete reporting groups of Atlantic salmon. The latest iteration reported in Bradbury *et al*. (2021) and used by ICES (2023) uses a panel of 96 Single Nucleotide Polymorphism (SNPs) to jointly distinguish 30 stock-units in the North Atlantic, 21 for NAC (including a NAC aquaculture group) and 10 for NEAC.

Five of the six NAC stock-units used to date by ICES each encompass several genetic reporting groups; the exception being USA which has a single reporting group (Table 4.4). With few exceptions, each individual genetic reporting group is contained within a single stock unit. Exceptions to this occur along boundaries of the stock-units, particularly between the Quebec and Gulf stock-units, the Gulf and Scotia-Fundy stock-units and to a lesser extent between Quebec and Labrador stock-units (Table 4.4; Figure 4.1).

For several stock-units, it would be possible to reconstruct returns and spawners to the finer scale genetic reporting groups beginning in 1984 and from 1971 to present for the regional reporting groups of Newfoundland, Gulf, Scotia-Fundy and USA. The exceptions are:

- The Quebec estimates prior to 1984 are presently available only at the scale of the province.
- For Labrador, the reconstruction of returns and spawners from 1971 to 1998 is based on the commercial catches from the Labrador region, estimates of exploitation and assumptions on the proportion of the harvests of Labrador origin (see run reconstruction details). It would not be possible with the current run reconstruction data to assess the three Labrador reporting groups defined in Bradbury *et al*. (2021).

Additional data would be required to partition into the regional reporting groups the coastal commercial fishery harvests from Quebec and the Maritime provinces prior to 1984, rather than attributing the commercial harvests from the coastal area of a region to the stock unit or regional group. There is also no information with which to partition the harvests in the Newfoundland (1971 to 1991) and Labrador (1971 to 1997) commercial fisheries to either the ICES stock-units or the finer scale regional reporting groups. In the PFA forecast and catch advice model, it is assumed that the stock unit contributions of these fisheries correspond to the proportions of the returns to the stock-units (see commercial fisheries harvest attributions). These issues may be resolvable using genetics and historical scale samples and could be considered based on future needs of life cycle modelling and catch advice for NASCO.

**Table 4.4. Reconciliation of ICES North American stock-units to management areas and genetic reporting groups based on microsatellites (Bradbury *et al*., 2014) and on a 96 SNP baseline (Bradbury *et al.,* 2021; ICES, 2023).**

<table>
<thead>
<tr><th rowspan="2">ICES stock unit</th><th rowspan="2">Management area</th><th colspan="2">ICES regional reporting group</th></tr>
<tr><th>Micro-satellites</th><th>SNP</th></tr>
</thead>
<tbody>
<tr><td>US</td><td>US</td><td>US</td><td>US</td></tr>
<tr><td rowspan="8">Scotia-Fundy</td><td rowspan="2">SFA 23</td><td>Gulf of St. Lawrence</td><td>Outer Bay of Fundy</td></tr>
<tr><td rowspan="4">Inner Bay of Fundy</td><td rowspan="2">Inner Bay of Fundy</td></tr>
<tr><td rowspan="3">SFA 22</td></tr>
<tr><td rowspan="2">Western Nova Scotia</td></tr>
<tr></tr>
<tr><td>SFA 21</td><td rowspan="2">Nova Scotia</td><td rowspan="2">Nova Scotia</td></tr>
<tr><td>SFA 20</td></tr>
<tr><td>SFA 19</td><td rowspan="5">Gulf of St. Lawrence</td><td rowspan="5">Gulf of St. Lawrence</td></tr>
<tr><td rowspan="5">Gulf</td><td>SFA 18</td></tr>
<tr><td>SFA 17</td></tr>
<tr><td>SFA 16</td></tr>
<tr><td rowspan="2">SFA 15</td></tr>
<tr><td rowspan="5">Gaspe</td><td rowspan="5">Gaspe</td></tr>
<tr><td rowspan="11">Quebec</td><td>Q1</td></tr>
<tr><td>Q2</td></tr>
<tr><td rowspan="2">Q3</td></tr>
<tr></tr>
<tr><td>Q5</td><td rowspan="3">Quebec</td><td rowspan="6">Quebec</td></tr>
<tr><td>Q6</td></tr>
<tr><td>Q7</td></tr>
<tr><td rowspan="2">Q8</td><td rowspan="5">Quebec / Labrador South</td></tr>
<tr></tr>
<tr><td rowspan="2">Q9</td></tr>
<tr><td rowspan="4">Labrador South</td></tr>
<tr><td rowspan="6">Labrador</td><td rowspan="2">SFA 14B</td></tr>
<tr><td rowspan="4">Labrador Central</td></tr>
<tr><td>SFA 2</td></tr>
<tr><td>SFA 1B</td><td>Central Labrador</td></tr>
<tr><td rowspan="2">SFA 1A</td><td rowspan="2">Northern Labrador</td></tr>
<tr><td rowspan="2">Ungava / Northern Labrador</td></tr>
<tr><td rowspan="2">Quebec</td><td>Q11</td><td>Ungava</td></tr>
<tr><td>Q10</td><td>Anticosti</td><td>Anticosti</td></tr>
<tr><td rowspan="15">Newfoundland</td><td>SFA 14A</td><td rowspan="5">Newfoundland</td><td rowspan="2">Northwest Newfoundland</td></tr>
<tr><td rowspan="2">SFA 3</td></tr>
<tr><td rowspan="4">Newfoundland 1</td></tr>
<tr><td>SFA 4</td></tr>
<tr><td>SFA 5</td></tr>
<tr><td>SFA 6</td><td rowspan="5">Avalon</td></tr>
<tr><td>SFA 7</td><td rowspan="4">Avalon</td></tr>
<tr><td>SFA 8</td></tr>
<tr><td>SFA 9</td></tr>
<tr><td rowspan="2">SFA 10</td></tr>
<tr><td rowspan="5">Newfoundland</td><td rowspan="2">Burin Peninsula</td></tr>
<tr><td rowspan="2">SFA 11</td></tr>
<tr><td>Fortune Bay</td></tr>
<tr><td>SFA 12</td><td>Newfoundland 2</td></tr>
<tr><td>SFA 13</td><td>Southwest Newfoundland</td></tr>
</tbody>
</table>

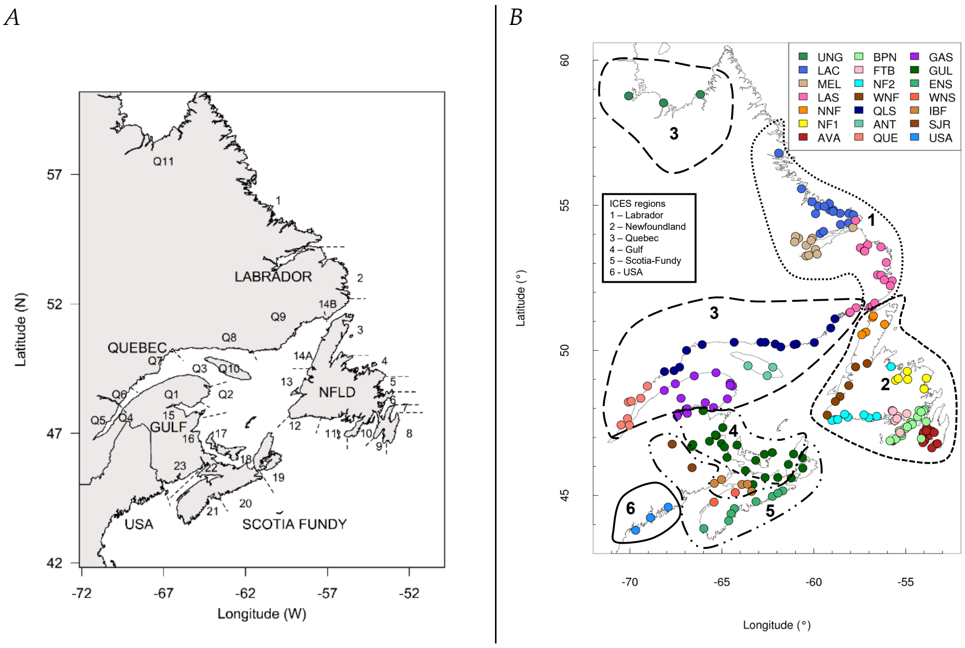


**Figure 4.1. A) Salmon Fishing Areas (SFA) and Quebec management zones (Q) for eastern Canada. B) Stock units for North American Atlantic Salmon used by ICES and the corresponding baseline samples of rivers and their attribution to genetic reporting groups based on SNPs (Bradbury *et al.*, 2021; ICES, 2023).**

## 4.2.2 Data inputs for the PFA forecast and LCM model

The run-reconstruction model developed by Rago *et al.* (1993) was originally intended to estimate the pre-fishery abundance (PFA) of non-maturing 1SW salmon of North American origin (beginning in 1971) for the purpose of providing forecasts of potential 2SW salmon abundance and advice for the West Greenland fishery. The focus on the non-maturing 1SW salmon component was because the West Greenland fishery exploits predominantly (>95%) 1SW non-maturing salmon (destined to return primarily as 2SW salmon). The other fish taken in the fishery represent 2SW and older non-maturing salmon and previous spawners (ICES 2023).

Subsequently, there was an increased interest in estimating returns, spawners and PFA for all sea-age groups (1SW maturing, 1SW non-maturing, 2SW) and the two reporting size groups (small salmon, large salmon). This allowed the presentation of stock status domestically and internationally and in the evolution of the models used by ICES to summarize stock status and provide catch advice for the West Greenland and potential Faroes fisheries.

The run-reconstruction concepts developed by Rago *et al.* (1993) were applied to these sea-age and size groups. ICES defined the two size groups as follows:

- Small salmon: in the recreational and subsistence fisheries refer to salmon less than 63 cm fork length. In historic commercial fisheries small salmon refer to fish less than 2.7 kg whole weight. The majority of the salmon in this size group are 1SW first time spawning salmon with a small proportion, depending upon geographic area, comprising other age groups including 2SW first time spawning salmon and repeat spawners. The small salmon category is used synonymously with 1SW (maturing) salmon.
- Large salmon: generally in recreational and subsistence fisheries are greater than or equal to 63 cm fork length. In historic commercial fisheries large salmon refer to fish greater than or equal to 2.7 kg whole weight. Salmon in this size category comprise a diverse sea-age and spawning history structure but in most geographic areas they are comprised of

a high proportion of 2SW and 3SW (very small proportions of older first-time spawning age groups) first time spawners and varying proportions of repeat spawners. In some areas of Newfoundland, the large salmon comprise a very high proportion of repeat spawners that first spawned as 1SW fish. In the Labrador commercial fisheries, the large salmon category was considered to include a proportion of 1SW non-maturing salmon, destined to have become 2SW salmon or older in the following year had they not been captured. These 1SW non-maturing salmon are included in a catch vector that is incorporated within the PFA and LCM models.

In contrast to the data inputs for the run reconstruction in the NEAC area, the inputs that are used to reconstruct returns and spawners for the six stock-units of NAC are provided as ranges of returns and spawners by jurisdictional experts, at sub-stock unit geographic scales. The returns in these assessment units were derived by applying a variety of methods to data available for individual river systems and management areas. These methods included counts of salmon at monitoring facilities, population estimates from mark-recapture studies and the application of angling and commercial catch statistics, angling exploitation rates and measurements of freshwater habitat to raise returns to assessment areas (Table 4.5; Stock Annex).

The run reconstruction of returns to the six stock-units of NAC represent stock unit abundances after the marine fisheries of Newfoundland, Labrador and Saint Pierre and Miquelon. Historically, the fisheries of Labrador (to 1997) and Newfoundland (to 1991) harvested salmon from all stock-units of eastern North America; the contemporary fishery of Saint Pierre and Miquelon (ongoing) harvests salmon from most regions of North America (ICES, 2023).

The time series of returns by size group and sea-age group for the six stock-units extend from 1970 (1971 for USA) to present. Descriptions of the input data by sub-stock unit used in the run reconstruction of returns and catches (spawners for the PFA models used by ICES) for the six stock-units of North America are summarized in Table 4.5 and summarized below. Details are provided in the NAC Stock Annex.

- USA: estimates of returns are provided for the stock unit as midpoint only for small salmon, large salmon and for 2SW salmon (subset of large salmon). These estimates of returns are derived from counts at fishways and from redd/spawner counts in smaller rivers. A narrow range of uncertainty (0.99 to 1.01 of midpoint) is added to give a minimum (min) to maximum (max) range for the stock unit. The time series extend from 1971 to present.
- Scotia-Fundy: return estimates are provided for two geographic areas (SFA 19-21, SFA 23). For SFA 19-21, returns to a monitored river are raised by ratio of recreational catches in the monitored river to catches in all SFA 19-21. For SFA 23, returns to the monitored river(s) are raised by habitat area of rivers in SFA 23. The SFA specific estimates of returns include the commercial harvests that occurred in the SFA. The time series extend from 1970 to present.
- Gulf: return estimates, with uncertainty range, are provided for 4 SFAs. The returns in each SFA are obtained from returns to SFA specific monitored rivers, raised by either ratios of recreational catches by SFA or by ratio of habitat area (SFA 16). The SFA specific estimates of returns include the commercial and Indigenous fisheries harvests that occurred in the SFA. The time series extend from 1970 to present.
- Quebec: return estimates to the stock unit are derived differently for two time periods. For 1970 to 1983, total returns to rivers, based on one of six categories of assessment, uncertainty are provided to which are added the commercial harvests and other losses outside the river returns. For 1984 to present, river-specific estimates of returns, with uncertainty ranges, are provided. An uncertainty range for each management zone (10 in total) is calculated as the sum of respective min to max ranges of rivers within each

zone. Annual commercial harvests and other losses outside the river are added to the annual stock unit total range. The time series extend from 1970 to present.

- Newfoundland: Estimates of returns to rivers are provided for each of the 11 SFAS in Newfoundland (SFA 3 to 14A). Returns are estimated from reported/estimated recreational fishery harvests of small salmon, raised by annual exploitation rates of small salmon harvests derived from rivers with monitoring facilities. Large salmon returns are estimated from the ratios of large salmon to small salmon at monitoring facilities, applied to estimated returns of small salmon. A non-parametric bootstrap with replacement is used to derive a min to max exploitation rate range and ratios of large to small salmon with the 95% confidence interval range used as the minimum and maximum estimates of returns. The time series extend from 1970 to present. Commercial harvests in the Newfoundland fishery are excluded from the estimates of returns to the Newfoundland stock unit.
- Labrador: For 1970 to 1997, estimates of returns were derived from the commercial harvests of salmon in the Labrador fishery adjusted by the estimated exploitation rate of the Labrador commercial fishery and with assumed proportions of Labrador origin salmon in the fishery harvests. For 2002 to present, returns to rivers of Labrador are derived based on returns to 3 or 4 monitored rivers, raised by ratios of watershed areas of monitored rivers to all salmon rivers of Labrador. For 1997 to 2001, as the commercial fishery was eventually closed and in the build-up of the monitoring rivers, returns were estimated from recreational fishery catches and exploitation rates in the recreational fishery of the years 2002 to 2008. The time series extend from 1970 to present. Commercial harvests of Labrador origin salmon in the Labrador fishery are excluded from the estimates of returns to the Labrador stock unit. A review of the run-reconstruction coding to derive returns to rivers of Labrador for 1SW and MSW sea-age groups should be done to ensure the reconstructions are consistent for the entire time-series.

### 4.2.3 Differences in the run-reconstruction to derive the stock unit inputs for the PFA model and for the LCM

The ICES WGNAS report (see ICES 2023 for example) presents and uses annual estimates of returns and spawners for small salmon, large salmon and 2SW salmon to characterize the stock status. PFA abundance estimates from run reconstruction were also presented for the corresponding size / sea-age groups for the NAC area. Spawners for each stock unit were derived using the run reconstruction model and sub-stock unit inputs of spawners provided by jurisdictional experts, using similar approaches described for the returns (see Table 4.5). Spawners are returns minus all losses in fisheries and include losses due to mortality of inriver caught and released salmon in recreational fisheries.

The PFA forecast model used by ICES until 2021 used estimates of returns and lagged spawners of the 2SW salmon component for each of the six stock-units, lagged to the pre-fishery abundance year (PFA of August 1 of the second summer at sea). The 2SW returns and spawners are a component of the large returns and these were derived using the sea-age composition of one or more indicator stocks. Lagged spawners, defined as spawners that would contribute recruitment at the PFA stage based on the proportion of the river age expected in each stock unit, are derived within the run-reconstruction model based on stock unit inputs of the expected smolt age proportions for an egg deposition year (see biological characteristics Section 4.2.5).

The LCM model does not require inputs of lagged spawners or eggs. The spawners are estimated from the returns and harvests inputs for each stock unit and their attribution to the year of PFA abundance occurs within the model based on the proportion smolt age vector or annual matrix provided for each stock unit.

The LCM model does require an input of harvests by size / sea-age group for each stock unit, which was previously not required from the run reconstruction for the PFA model. For NAC, sub-stock unit inputs continue to be in terms of returns and spawners. From these, harvests (total losses in fisheries) are derived as the difference between returns and spawners; the run reconstruction code has been modified to do this calculation and point estimates of the harvests are derived as the difference of the medians of the MCMC distributions of returns and spawners.

For the USA stock unit, spawners may exceed returns in some years due to hatchery programs. An additional input to the LCM is a vector of stocked spawners that accounts for the contribution of captive-reared salmon released to the wild to spawn.

### 4.2.4 Changes to the LCM inputs from the previous version

To harmonize the LCM structure between the NAC and NEAC areas, it was decided to consider the two sea-age groups as 1SW and MSW, rather than 1SW and 2SW as was done previously for NAC. Based on extensive sampling across stock-units in NAC, the small salmon size category is considered equivalent to the 1SW sea-age component. The large salmon category, which would include 1SW (in very low proportions), 2SW, 3SW and older first time spawner ages as well as repeat spawning salmon, is considered equivalent to MSW salmon. Corresponding biological characteristics for the 1SW and MSW components were revised accordingly when warranted (see biological characteristics, Section 4.2.5).

**Table 4.5. Summary of input data and derivation of uncertainties used in the run reconstruction of returns to the six stock-units of NAC.**

| Stock unit | Year range | Parameter or data input to run reconstruction | Min to max range |
|---|---|---|---|
| USA | 1971 to present | Returns of small salmon, large salmon, 2SW salmon overall for USA | Midpoint only (narrow range of uncertainty added, 0.99 to 1.01 of midpoint) |
| Canada – Scotia-Fundy (SF) | 1970 to present | Returns of small salmon, large salmon, 2SW salmon for two geographic areas (SFAs 19-21, SFA 23)<br>- Includes commercial harvests of salmon that occurred in adjoining waters of the SFAs<br>- 2SW salmon estimated from large salmon based on a fixed proportion of 2SW in large salmon | Provided as min to max range for two geographic areas |
| Canada – Southern Gulf of St Lawrence (GULF) | 1970 to present | Returns of small salmon, large salmon, 2SW salmon for 4 SFAs (15 to 18)<br>- Includes commercial and Indigenous fisheries harvests of salmon that occurred in adjoining waters of the SFAs<br>- 2SW salmon estimated from large salmon based on a fixed proportion of 2SW in large salmon for SFAs 15, 17 and 18 and annually derived proportion from sampling in SFA 16 | Provided as min to max range by SFA |
| Canada – Quebec (QC) | 1971 to 1983 | Annual returns of small salmon and large salmon by assessment category for all of Quebec.<br>- commercial harvests of salmon in jurisdictional waters of the province of Quebec added to the total returns of Quebec<br>- 2SW salmon estimated based on fixed proportion of 2SW salmon in the large salmon category. | Provided as min to max estimates of returns and spawners |
| | 1984 to present | River specific estimates of returns of small salmon and large salmon are used to derive min to max ranges for 11 fishing zones (1 to 11)<br>- commercial harvests of salmon in jurisdictional waters of the province of Quebec added to the total returns of Quebec<br>- 2SW salmon estimated based on fixed proportion of 2SW salmon in the large salmon category. | Min to max range by river summed to give min to max range by zone (10 zones in total) |

| Stock unit | Year range | Parameter or data input to run reconstruction | Min to max range |
|---|---|---|---|
| Canada – Newfoundland (NFLD) | 1971 to present | Annual returns of small salmon, large salmon and 2SW salmon for 12 SFAs (3 to 14A)<br>- exploitation rates in the recreational fishery for retained small salmon are derived from angling harvests in monitored rivers, exploitation rate uncertainty derived annually from available exploitation rates in monitored rivers<br>- exploitation rate range for retained small salmon is used to estimate returns of small salmon based on angling harvest (retained) of small salmon<br>- returns of large salmon estimated from annual ratios of large to small salmon from monitored rivers<br>- 2SW salmon estimated based on fixed 2SW proportion in large salmon, by SFA | non-parametric bootstrap technique, with replacement, 95% C.I. used to derive min to max range by SFA (11 in total) |
| Canada – Labrador (LAB) | 1971 to 1996 | Annual commercial harvests of small salmon, large salmon for 3 SFAs (1,2,14B)<br>Annual exploitation rates by size group by SFA similar for 1971 to 1991, then adjusted for reductions in active licences, closure of Newfoundland commercial fishery since 1992 and changes in fishing seasons in Labrador after 1994 | Point estimates in number of fish by size group<br>Exploitation rates based on recaptures of tagged smolts from Sand Hill River (1969 to 1971) , recovered in the Newfoundland and Labrador commercial fisheries |
| | | Proportion of large salmon that are 2SW salmon | By SFA; 0.6 to 0.8 or 0.7 to 0.9 |
| | | Proportion of 1SW salmon in the large salmon category of the commercial catches | 0.1 to 0.3 |
| | | Proportion of all 1SW salmon in commercial catches that are non-maturing | 0.1 to 0.2 |
| | | Proportion Labrador origin of commercial catch of | 0.6 to 0.8 |
| | 1997 | Commercial harvest number in SFA 1 and 2 (closed in SFA 14B)<br>Adjusted exploitation rate in SFA 1, 2 based on reductions in licenced effort<br>Biological characteristics parameters as for 1970 to 1996 | Range derived as for 1970 to 1996 |
| | | For SFA 14B, returns estimated as the sum of returns to 2 monitored rivers raised by watershed areas of rivers in SFA 14B | Range provided by expert opinion |
| | 1998 to 2001 | Recreational fishery catches and exploitation rates.<br>- Return estimates of small and large salmon for 2002 to 2008, from monitoring of 3 to 4 rivers and raised by watershed areas of rivers in Labrador, were used to derived exploitation rates of small retained fish and large retained plus hooked-and-released in the Labrador recreational fishery. The range of these exploitation rates for the years 2002-2008 was applied to the angling catches in 1998-2001 to provide estimates of returns for 1998 to 2001. | Provided as min to max estimates of returns. |
| | 2002 to present | Annual returns to rivers of Labrador for small salmon and large salmon<br>- return by size group per drainage area of 3 to 4 monitored rivers used to raise to all rivers of Labrador based on total drainage areas of rivers | non-parametric bootstrap technique, with replacement, 95% C.I. used to derive min to max |
| | | Proportion 2SW in large salmon returns to rivers | 0.60 to 0.71 |

### 4.2.5 Biological characteristics

Updates were made in 2021 to the historical values of fecundities and other biological characteristics of small and large salmon in each of the stock-units in NAC (Table 4.6) and further update was provided by USA in 2023. Additionally, the methods used to up-scale values from individual Salmon Fishing Areas (SFAs) and Management Zones (Qs) to regional values for Quebec, Gulf and Scotia-Fundy were more formally documented (NAC Stock Annex). These biological characteristics are required as input to the lifecycle model. Currently, fixed values are used for the entire biological time series (Table 4.6).

The smolt age proportions reflect stock-specific populations dynamics and the freshwater environment that modify the freshwater survival rates, precocious maturation rates and the probabilities of smoltifying at age. These freshwater / stock conditioned smolt age proportions by egg year class would likely not be the same as the annual smolt age proportions of returning anadromous salmon. However, absent such information for each stock unit, the smolt age proportions assumed for the stock-units were derived from a large database of available smolt ages from sampled returning salmon over a large number of years and are considered to be the most appropriate values for the stock-units of NAC. No changes were made to the smolt age proportions by stock unit from those used for the PFA forecast model (Table 4.6). Two vectors of smolt age proportions are defined for the USA stock unit for two time periods; 1971 to 1989, 1990 to present. The change for the USA stock unit was made in 2004 to reflect declines in natural spawning and changes in hatchery and stocking practices (ICES 2005). ICES (2005) also reported on examination of smolt ages for the Labrador and Gulf stock unit and concluded that there was insufficient evidence to warrant changing the smolt age proportions at that time.

The smolt age proportions previously defined are assumed to apply to all the eggs, regardless of sea-age origin, for the LCM.

**Table 4.6. Biological characteristics inputs by sea-age group for the six stock-units of NAC.**

| Parameter | Age group | Stock unit | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | USA | | SF | GULF | QC | NFLD | LAB |
| Eggs per female | 1SW | 3165 | | 3194 | 3354 | 3618 | 2500 | 2500 |
| | MSW | 7829 | | 6434 | 7979 | 8479 | 5000 | 5000 |
| Prop. female | 1SW | 0.0109 | | 0.350 | 0.113 | 0.140 | 0.859 | 0.505 |
| | MSW | 0.64 | | 0.889 | 0.740 | 0.670 | 0.804 | 0.859 |
| Eggs per fish | 1SW | 3165 | | 1119 | 379 | 496 | 1782 | 1262 |
| | MSW | 7829 | | 5722 | 5904 | 5653 | 4180 | 4295 |
| Smolt age Prop. | | 1971-1989 | 1990-present | | | | | |
| | Smolt age 1 | 0.3767 | 0.6274 | 0 | 0 | 0 | 0 | 0 |
| | Smolt age 2 | 0.5200 | 0.3508 | 0.6002 | 0.3979 | 0.0577 | 0.0408 | 0 |
| | Smolt age 3 | 0.1033 | 0.0218 | 0.3942 | 0.5731 | 0.4644 | 0.5979 | 0.0768 |
| | Smolt age 4 | 0 | 0 | 0.0055 | 0.0291 | 0.3783 | 0.3237 | 0.5420 |
| | Smolt age 5 | 0 | 0 | 0 | 0 | 0.0892 | 0.0375 | 0.3410 |
| | Smolt age 6 | 0 | 0 | 0 | 0 | 0.0104 | 0 | 0.0401 |

## 4.2.6 Conservation Limits for NAC

For the provision of catch advice for the West Greenland fisheries, ICES (2002) defined the conservation limits for six North American stock-units, in number of fish, for the two-sea-winter sea-age component only. This was done to support the catch advice for the West Greenland fishery, which exploited primarily 1SW non-maturing salmon, the majority of which would have likely returned to North America as 2SW first time spawners. In addition to the Conservation Limits, ICES (2002) also provided management objectives for the two southern stock-units of Scotia-Fundy and USA. The management objectives were defined in recognition that these stock-units were at such low abundance that there was no probability that returns would equal or exceed the CLs even in the absence of fishing at West Greenland or in homewaters. The management objectives, in terms of 2SW salmon spawners, were described as rebuilding objectives.

Conservation limits in terms of total eggs, or in terms of small salmon and large salmon, for the six stock-units of NAC have not been previously defined by ICES. In the interest to move to a life cycle model (LCM) with total eggs as the starting point of the life cycle, there is a need to define the conservation limits in units of total eggs and to provide the equivalences of the total eggs in terms of 1SW and MSW salmon, accounting for the biological characteristics of the two size groups and the anticipated or desired sea-age proportions of the eggs.

The Limit Reference Point (LRP; Table 4.7) is considered equivalent to the CLs for purpose of assessing stock status and providing catch advice with the LCM. The LRPs are defined in terms of eggs from all sea-age groups of spawners. The total eggs are converted to number of fish equivalents of 1SW and MSW salmon based on biological characteristics of the salmon, weighted by the desired relative proportions of the sea-age groups in the returns to rivers.

The equations for translating total egg CL requirements to sea-age equivalencies (1SW, MSW) require the following input data:

| | |
|---|---|
| $\mathrm{CL_{eggs}}$ | Conservation limit in total eggs |
| $\mathrm{Fec}_a$ | Fecundity of a female spawner in eggs per kg by sea-age category *a* (1SW, MSW) |
| $u.\mathrm{kg}_a$ | Mean weight (kg) of female spawner by sea-age category a |
| $p.\mathrm{Fem}_a$ | Proportion female by sea-age category *a* |
| $p.\mathrm{MSW}$ | Proportion of eggs contributed by MSW salmon |

The calculation of equivalencies of CL eggs into spawner numbers by sea-age ($\mathrm{CL}_a$) is:

$$\mathrm{CL_{MSW}} = \frac{\mathrm{CL_{eggs}} * p.\mathrm{MSW}}{\mathrm{Fec_{MSW}} * u.\mathrm{kg_{MSW}} * p.\mathrm{Fem_{MSW}}}$$

$$\mathrm{CL_{1SW}} = \frac{\mathrm{CL_{eggs}} * (1 - p.\mathrm{MSW})}{\mathrm{Fec_{1SW}} * u.\mathrm{kg_{1sw}} * p.\mathrm{Fem_{1SW}}}$$

The proportion of eggs contributed by MSW salmon within any year is calculated from the estimated abundance of each age group (*N*.1SW, *N*.MSW):

$$p.\mathrm{MSW} = \frac{N.\mathrm{MSW} * \mathrm{Eggs_{MSW}}}{N.\mathrm{MSW} * \mathrm{Eggs_{MSW}} + N.\mathrm{1SW} * \mathrm{Eggs_{1sw}}}$$

Where:

| | |
|---|---|
| $N.\mathrm{MSW}$ | Number of MSW spawners, |
| $\mathrm{Eggs_{MSW}}$ | Eggs per MSW spawner = $\mathrm{Fec_{MSW}} * u.\mathrm{kg_{MSW}} * p.\mathrm{Fem_{MSW}}$, |
| *N*.1SW | Number of 1SW spawners and |
| $\mathrm{Eggs_{1SW}}$ | Eggs per 1SW spawner = $\mathrm{Fec_{1SW}} * u.\mathrm{kg_{1SW}} * p.\mathrm{Fem_{1SW}}$ |

In terms of CLs which are intended to represent production potential based on demographics, life history and populations dynamics considerations, we would be more interested in characterizing the egg contributions from the recruitment (non-fished characteristics), by sea-age groups by egg year classes if possible, but minimally by smolt cohort.

For NAC, the conversions from total eggs to fish has used estimates of sea-age proportions from inriver returns (i.e. prior to inriver fisheries but after marine fisheries) although this is not always clearly stated. CLs in terms of fish equivalents by sea-age group are subject to further review and adoption by NAC countries.

Details of stock unit estimates of CLs are in the NAC Stock Annex and summarized in Table 4.7 and Table 4.8.

- USA: The CL is based on an egg deposition rate of 240 eggs per 100 $m^2$ of estimated accessible fluvial rearing habitat. The calculation assumes a 50:50 ratio of males to females and a mean fecundity of 7,200 eggs per female. The CL only considers 2SW fish, but this is not considered a major issue given the extremely low proportion of 1SW, 3SW and repeat female spawners within the Unites States (USASAC 2022). The CL is considered a minimum estimate, but represents the best available estimate at this time. Considering the extremely depleted state of USA populations, an alternative Management Objective was also established (NASCO 2013), which aligns with the recovery criteria for the remnant stocks currently under federal protection. The CL and Management Objective are summarized in Table 4.8.
- Scotia-Fundy: The LRP is based on an egg deposition rate of 240 eggs per 100 $m^2$ of fluvial rearing habitat. The egg conservation limits and the corresponding number of fish are summarized in Table 4.8. The proportion of the desired egg contributions from 1SW and MSW salmon were tabled by Gibson and Claytor (2013); it is assumed that the desired proportions by sea-age are based on returns to rivers (prior to inriver fisheries).
- Gulf: The LRP is defined as the egg deposition that would result in a low probability (< 25%) of the smolt production being less than half of the asymptotic production based on a Beverton-Holt stock and recruitment model with a covariate that accounts for the proportion of the eggs that would be deposited by large salmon; as the proportion of eggs deposited by large salmon increases, the optimal egg deposition rate decreases. Egg deposition rates for the rivers of Gulf vary from 152 eggs per 100 $m^2$ (prop. of eggs from large > 0.90) to 176 eggs per 100 $m^2$ (prop. of eggs from large = 0.78) (DFO 2018). The total LRP in terms of eggs is converted to number of fish by sea-age equivalents using the average biological characteristics of the small salmon and large salmon returns (**Table 4.8**).
- Quebec: A Bayesian hierarchical model (adult to adult eggs; Ricker SR function) with reference points transported to individual rivers based on estimated habitat within the model was used to define reference points for 105 rivers in Québec. A limit reference point (LRP) was selected as the spawner abundance equivalent to the 75$^{th}$ percentile of the posterior distribution of $S_{0.5Rmax}$ (spawner abundance at 50% maximum recruitment).
- Egg depositions from all sea-age groups are included in the assessment of status relative to the LRP. Catch advice of the West Greenland and homewater fisheries would be provided relative to the LRP defined in terms of eggs. The total LRP in terms of eggs is converted to number of fish by sea-age equivalents using the average biological characteristics of the small salmon and large salmon returns (Table 4.8). The definition of the 2SW conservation limit for Quebec is revised from ICES (2023) to correspond to the defined LRP.
- Newfoundland: Conservation egg requirements are defined as the product of the number of fluvial habitat units (unit = 100 $m^2$) and an egg deposition rate of 240 eggs per unit plus the product of the number of hectares of lacustrine habitat and an egg deposition rate of 368 eggs per ha or 175 eggs per ha for the rivers of SFA 14A, the Northern Peninsula of Newfoundland (O'Connell and Dempson 1995; DFO 2015). O'Connell *et al.* (1997) provide spawner requirements in terms of small salmon, large salmon and for 2SW sea-age group for each of the SFAs in Newfoundland. Based on average eggs per fish by size group (Table 4.7), the total egg requirement equivalent to the conservation limit for Newfoundland would be 417.78 million eggs (Table 4.8).

- Labrador: The methods for deriving the conservation limits (referred to at the time as spawner targets) used by ICES for 2SW salmon, large salmon and small salmon are described in O'Connell *et al*. (1997) and the stock annex. The conservation limits in terms of number of fish were defined from the ratio of spawners to recruits (in the absence of marine fisheries) of Labrador salmon. The recruits were estimated from the run reconstruction of returns to Labrador, to which was added the catch of Labrador origin 1SW non-maturing salmon at West Greenland, corrected for 10 months of mortality (at a rate of 1% per month) between the start of the West Greenland fishery (Aug. 1) and the returns to the coast of Labrador (June 1). The period of returns to Labrador during 1974 to 1978 and West Greenland catches during 1973 to 1977 was chosen as the reference period to define the mean recruitment potential of the Labrador stock unit. Recently, Reddin *et al.* (2006) provide background and justification for the definition of a conservation limit egg deposition rate of 190 eggs per 100 m² of fluvial parr rearing habitat for rivers of Labrador, based on analysis of stock and recruitment data from the Sand Hill River with the conservation limit equivalent to the egg deposition that corresponds to 50% of the equilibrium point (eggs in recruitment equal eggs in spawners) of a fished population (mean return rate of smolts to the river as spawners of 0.073; Reddin *et al.* 2006). Reddin *et al.* (2010) list 89 rivers in Labrador (SFAs 1, 2 and 14B) and their associated egg requirements to meet conservation limits. The total egg requirement of these 89 rivers is 239.14 million eggs (Table 4.8). Average biological characteristics by size group are in Table 4.8. As a first estimate of the proportion of the eggs contributed by large salmon in Labrador, we considered the ratio of eggs contributed by large salmon based on the estimated recruits of small salmon and large salmon to Labrador as described above.

**Table 4.7. Atlantic Salmon reference points that equate to conservation limits for the stock-units within the North American Commission area of NASCO.**

| NAC Region | Objective | Reference Point | Reference |
|---|---|---|---|
| USA | Egg deposition to fully seed the estimated fluvial accessible rearing habitat | 240 eggs per 100 m² of fluvial habitat | Baum (1995) |
| Scotia-Fundy | LRP: egg depositions that result in half of maximum smolt production, Beverton-Holt function | LRP: 240 eggs per 100 m² of fluvial habitat | Gibson and Claytor (2013) |
| Gulf | LRP: egg depositions that result in a low probability (<25%) of smolt recruitment being less than 50% of maximum recruitment (Beverton-Holt function)<br>Upper Stock Reference point (USR): eggs in recruitment at MSY | Depends on river-specific sea-age characteristics of spawners;<br>LRP: 152 to 178 eggs per 100 m² of fluvial habitat<br>USR: LRP * 3.78 | DFO (2015, 2018, 2022); Chaput *et al.* (2023) |
| Québec | LRP1: egg depositions that result in a high probability (75th percentile of posterior distribution) of the adult recruitment being more than 50% of maximum recruitment (Ricker function)<br>LRP2: egg deposition allowing to preserve 90% of the genetic diversity over 100 years. River not reaching this genetic conservation limit are classified below all reference point<br>USR: egg depositions that result in a very high probability (95th percentile of posterior distribution) of the adult recruitment being more than MSY ( Ricker function) | LRP varies depending upon productive units of river (average 132 eggs per 100 productive units of fluvial habitat)<br>USR: varies depending upon productive units of river (average 312 eggs per 100 productive units of fluvial habitat) | Dionne *et al.* (2015);<br>MFFP (2016) ;<br>Ferchaud *et al.* (2016) |

| NAC Region | Objective | Reference Point | Reference |
|---|---|---|---|
| Insular Newfoundland | LRP: maximum freshwater production, miscellaneous approach<br>USR: defined as 1.5 * LRP | LRP: 240 eggs per 100 $m^2$ fluvial habitat + 368 eggs per ha of lacustrine habitat or +150 eggs per ha of lacustrine habitat for the Northern Peninsula (SFA 14A) | Anon. 1991; O'Connell and Dempson (1995); USR: DFO (2020) |
| Labrador | LRP: eggs for 50% of adult equilibrium point for a fished population, Beverton-Holt function | 190 eggs per 100 $m^2$ of fluvial habitat | Reddin *et al.* (2006) |

**Table 4.8. CLs for stock-units of NAC in units of total eggs and equivalences in number of 1SW and MSW salmon to be used in the LCM for provision of catch advice for NASCO. The 2SW salmon CL and the management objectives are from ICES (2023) with updated values.**

| Stock unit | Conservation limits | | | | Management objective |
|---|---|---|---|---|---|
| | Eggs (million) | 1SW salmon (fish) | MSW salmon (fish) | 2SW (updated) | 2SW |
| USA | na | na | na | 29,199 | 4,549 |
| Scotia–Fundy | 253.529 | 77,565 | 30,484 | 24,785 | 10,976 |
| Gulf | 171.815 | 27,943 | 27,395 | 18,737 | |
| Quebec | 124.604* | 21,047* | 21,077* | 32,085 (18 914) | |
| Newfoundland | 417.78 | 198,160 | 15,468 | 4,022 | |
| Labrador | 239.14 | 55,806 | 39,281 | 34,746 (28,310) | |

* Excludes values for the four northern rivers of Ungava Bay (management zone Q11)
na – not available at time of writing owing to updates and access, to be confirmed in the Stock Annex.

# 4.3 Mixed stock marine fisheries

Harvests and biological characteristics of salmon in marine mixed stock fisheries are provided as annual inputs for the PFA forecast model and for the LCM. Three marine fisheries of the Northwest Atlantic (Labrador, Newfoundland and Saint Pierre and Miquelon) only intercept salmon from the NAC stock-units. Two marine mixed stock fisheries, Greenland and Faroes), affect salmon from both NAC and NEAC stock-units. Further descriptions and time series of these fisheries are provided in the ICES Stock Annex.

## 4.3.1 Marine fisheries affecting only NAC stock-units

The commercial salmon fishery in Newfoundland has been under moratorium since 1992. The Labrador commercial salmon fishery closed in 1998 but there is an ongoing coastal subsistence food fishery since 1998. There is a gillnet fishery for salmon in the territorial waters of France around the islands of Saint Pierre and Miquelon. The commercial harvests (and subsistence fishery harvests since 1998 in Labrador) are provided in numbers of small salmon and large salmon for two large areas of Newfoundland and for three Salmon Fishing Areas of Labrador (Table 4.9; Table 4.10).

The run reconstruction of returns to the six stock-units of NAC represent abundances after the marine fisheries of Newfoundland, Labrador and Saint Pierre and Miquelon, therefore the attribution of origin of the catches is not required for the run reconstruction step to estimate returns (except for the estimation of returns to rivers of Labrador which assumes a proportion of the commercial harvests are of Labrador origin).

Attribution of the harvests in the Labrador, Newfoundland and Saint Pierre and Miquelon marine fisheries to the NAC stock-units is done in the PFA forecast model (specifically for 2SW salmon) and in the LCM; for both based on assumptions of availabilities of the stock-units to those fisheries.

For Labrador: The commercial harvest number of small salmon, large salmon are tabulated by SFA for Labrador. For the subsistence fisheries since 1998, the harvests by size group are tabulated for the combined SFAs of Labrador.

- Labrador commercial fishery harvests of small salmon and large salmon for 1971 to 1997 are considered to comprise 60% to 80% Labrador origin fish, with the remainder attributed to the other five stock-units in proportion to the sum of the PFA for those five stock-units.
- Labrador subsistence (Indigenous Food, Social and Ceremonial fisheries, Labrador resident food fisheries) fishery harvests for 1998 to present are considered to comprise 90% to 100% Labrador origin fish, with the remainder (0 - 10%) attributed to the other five stock-units in proportion to the sum of the PFA for those five stock-units.
- Proportion 2SW salmon in the large salmon category is assumed 0.6 to 0.8 or 0.7 to 0.9, by SFA for 1971 to 1997. For the subsistence fisheries of 1998 to present, the proportion 2SW in the harvests is assumed to be 0.60 to 0.71.

For Newfoundland: The harvest number of small salmon, large salmon are tabulated for two regions of the Newfoundland coast, the northeast region comprised of SFAs 3 to 7 and the south and west coast comprised of SFAs 8 to 14A.

- Harvests of salmon in the SFAs 3 to 7 region are attributed to the six stock-units of NAC based on the proportion of the estimated stock unit PFAs, including Labrador.
- For SFAs 8 to 14A, it is assumed that no Labrador origin salmon are harvested in those fisheries and the harvests are attributed to the other five stock-units in proportion to the sum of their estimated stock unit specific PFAs.
- The proportion 2SW in the large salmon category is assumed to be 0.7 to 0.9 for the harvests in SFA 3 to 7. All large salmon are assumed to be 2SW salmon in the harvests from SFAs 8 to 14A.

For Saint Pierre and Miquelon: Harvests in total weight are converted to number of small and large salmon based on samples (limited in many years) from the fishery. Salmon harvested by the Saint Pierre and Miquelon salmon fishery have been attributed to all stock-units of eastern North America, although few have been identified from Labrador or the USA (ICES 2021, 2023).

- It is assumed that no Labrador origin salmon are harvested in this fishery and the harvests are attributed to the other five stock-units in proportion to the sum of their estimated stock unit specific PFAs.
- All large salmon are assumed to be 2SW salmon.

### 4.3.2 Marine fisheries affecting NAC and NEAC stock-units

*Faroes fishery*

The fishery in the Faroes area commenced in 1968 with a small number of vessels fishing up to 70 miles north of the Faroes. Catches peaked at 1025 tonnes in 1981. There has been no commercial salmon fishery targeting salmon around the Faroes since the early 1990s.

The Faroes salmon fishery operated from November through to May. The salmon caught in the fishery originated almost entirely from European countries with salmon from many countries being present in the area although small numbers of tagged fish originating in North America were also recaptured in the fishery.

The fishery exploited mainly 2SW fish, although some 1SW and 3SW fish were also caught. Small salmon (<60 cm total length) in their first winter at sea were required to be discarded. Large numbers of farmed salmon were also observed at Faroes and farmed fish accounted for a significant proportion of the catch; in the early 1990s, the proportion of farmed fish in this area was estimated at between 25 and 40% (Hansen *et al*., 1999).

Inputs to the run reconstruction, PFA forecast model and for the LCM consist of estimated number of 1SW salmon, MSW salmon captured in the fishery (by year), percentages of 1SW salmon catch that is unreported (and associated % uncertainty of this value) and the proportion of the catch that was wild salmon (i.e. not farmed escapee origin) (**Table 4.11**). The time series of data for this fishery extends from 1971 to 2022.

Other multi-annual data include mid-month of returns to stock-unit, estimates of catch proportions by stock-unit of origin in the Faroes fisheries, mid-point month of fishery-catch and associated variation and mortality proportion of released/discarded fish for Faroes.

*Greenland fishery*

Limited fishing at West Greenland is reported as far back as the early 1900s, although the present fishery dates from 1959. Rapid expansion along the coast followed and was associated with changes in gear technology, resulting in a maximum reported landing of almost 2700 tonnes in 1971. Small catches of salmon are also made on the east coast of Greenland although these are sporadic and low and are not included in the run reconstruction or PFA modelling by ICES.

Regulatory measures agreed by the West Greenland Commission of NASCO resulted in greatly reduced allowable catches in the West Greenland fishery, reflecting declining abundance of the contributing salmon stocks. In all but two years since 1998, the fishery has been restricted to an internal-use fishery and commercial export of salmon has not been permitted.

The Greenland salmon fishery operates in summer, generally August through October, with a fairly large proportion of the catch commonly being taken in the weeks after the opening of the season in August. The salmon caught at West Greenland are almost exclusively fish in their second summer at sea: non-maturing 1SW salmon destined to return to homewaters as 2SW, or older, fish. Fish from all parts of North America are taken in the fishery, while it is primarily only potential MSW salmon from southern countries in Europe (UK, Ireland and France) that are exploited here. Very few salmon of farmed origin appear in the catches at Greenland and these are not taken into account in assessments.

Inputs to the run reconstruction, PFA forecast model and for the LCM consist of reported catch weight at West Greenland, best estimates of unreported catch weight and biological characteristics of sampled salmon to convert catch in weight to catch in number of NAC and NEAC origin salmon. The time series of data for this fishery extends from 1971 to 2022 (**Table 4.12**).

Other multi-annual data include mid-month of returns to stock-unit and mid-point month of fishery-catch and associated variation.

**Table 4.9. Harvests (number of fish) of large salmon in the marine fisheries of Labrador (LAB), Newfoundland (NFLD) and Saint Pierre and Miquelon (SPM), 1970 to 2022.**

| Year | LAB | | | | NFLD | | SPM |
|---|---|---|---|---|---|---|---|
| | SFA 01 | SFA 02 | SFA 14B | Subsistence | SFA 3-7 | SFA 8-14A | |
| 1970 | 17633 | 45479 | 9595 | 0 | na | na | 0 |
| 1971 | 25127 | 64806 | 13673 | 0 | 81152 | na | 0 |
| 1972 | 21599 | 55708 | 11753 | 0 | 43041 | 42861 | 0 |
| 1973 | 30204 | 77902 | 16436 | 0 | 85904 | 43627 | 0 |
| 1974 | 13866 | 93036 | 15863 | 0 | 73961 | 85714 | 0 |
| 1975 | 28601 | 71168 | 14752 | 0 | 100504 | 72814 | 0 |
| 1976 | 38555 | 77796 | 15189 | 0 | 79318 | 95714 | 348 |
| 1977 | 28158 | 70158 | 18664 | 0 | 114413 | 63449 | 0 |
| 1978 | 30824 | 48934 | 11715 | 0 | 64073 | 37653 | 0 |
| 1979 | 21291 | 27073 | 3874 | 0 | 29936 | 29122 | 0 |
| 1980 | 28750 | 87067 | 9138 | 0 | 86941 | 54307 | 0 |
| 1981 | 36147 | 68581 | 7606 | 0 | 98672 | 38663 | 0 |
| 1982 | 24192 | 53085 | 5966 | 0 | 46076 | 35055 | 0 |
| 1983 | 19403 | 33320 | 7489 | 0 | 48218 | 28215 | 348 |
| 1984 | 11726 | 25258 | 6218 | 0 | 44540 | 15135 | 348 |
| 1985 | 13252 | 16789 | 3954 | 0 | 36975 | 24383 | 348 |
| 1986 | 19152 | 34071 | 5342 | 0 | 48996 | 22036 | 290 |
| 1987 | 18257 | 49799 | 11114 | 0 | 67072 | 19241 | 232 |
| 1988 | 12621 | 32386 | 4591 | 0 | 36449 | 14763 | 232 |
| 1989 | 16261 | 26836 | 4646 | 0 | 37576 | 15577 | 232 |
| 1990 | 7313 | 17316 | 2858 | 0 | 31847 | 11639 | 218 |
| 1991 | 1369 | 7679 | 4417 | 0 | 25792 | 10259 | 135 |
| 1992 | 9981 | 19608 | 2752 | 0 | 0 | 0 | 269 |
| 1993 | 3825 | 9651 | 3620 | 0 | 0 | 0 | 342 |
| 1994 | 3464 | 11056 | 857 | 0 | 0 | 0 | 398 |
| 1995 | 2150 | 8714 | 312 | 0 | 0 | 0 | 97 |
| 1996 | 1375 | 5479 | 418 | 0 | 0 | 0 | 182 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1997 | 1393 | 5550 | 263 | 0 | 0 | 0 | 173 |
| 1998 | 0 | 0 | 0 | 2269 | 0 | 0 | 268 |
| 1999 | 0 | 0 | 0 | 1084 | 0 | 0 | 270 |
| 2000 | 0 | 0 | 0 | 1352 | 0 | 0 | 263 |
| 2001 | 0 | 0 | 0 | 1721 | 0 | 0 | 250 |
| 2002 | 0 | 0 | 0 | 1389 | 0 | 0 | 227 |
| 2003 | 0 | 0 | 0 | 2175 | 0 | 0 | 348 |
| 2004 | 0 | 0 | 0 | 3696 | 0 | 0 | 196 |
| 2005 | 0 | 0 | 0 | 2817 | 0 | 0 | 351 |
| 2006 | 0 | 0 | 0 | 3090 | 0 | 0 | 469 |
| 2007 | 0 | 0 | 0 | 2652 | 0 | 0 | 218 |
| 2008 | 0 | 0 | 0 | 3909 | 0 | 0 | 442 |
| 2009 | 0 | 0 | 0 | 3344 | 0 | 0 | 408 |
| 2010 | 0 | 0 | 0 | 3725 | 0 | 0 | 470 |
| 2011 | 0 | 0 | 0 | 4451 | 0 | 0 | 1031 |
| 2012 | 0 | 0 | 0 | 4228 | 0 | 0 | 156 |
| 2013 | 0 | 0 | 0 | 6479 | 0 | 0 | 1272 |
| 2014 | 0 | 0 | 0 | 3994 | 0 | 0 | 611 |
| 2015 | 0 | 0 | 0 | 6146 | 0 | 0 | 410 |
| 2016 | 0 | 0 | 0 | 5595 | 0 | 0 | 286 |
| 2017 | 0 | 0 | 0 | 5818 | 0 | 0 | 78 |
| 2018 | 0 | 0 | 0 | 4077 | 0 | 0 | 214 |
| 2019 | 0 | 0 | 0 | 5793 | 0 | 0 | 182 |
| 2020 | 0 | 0 | 0 | 6345 | 0 | 0 | 214 |
| 2021 | 0 | 0 | 0 | 4217 | 0 | 0 | 241 |
| 2022 | 0 | 0 | 0 | 5035 | 0 | 0 | 152 |

**Table 4.10. Harvests (number of fish) of small salmon in the marine fisheries of Labrador (LAB), Newfoundland (NFLD) and Saint Pierre and Miquelon (SPM), 1970 to 2022.**

| Year | LAB | | | | NFLD | | SPM |
|---|---|---|---|---|---|---|---|
| | SFA 01 | SFA 02 | SFA 14B | Subsistence | SFA 3-7 | SFA 8-14A | |
| 1970 | 14666 | 29441 | 8605 | 0 | NA | NA | 0 |
| 1971 | 19109 | 38359 | 11212 | 0 | 111518 | 70936 | 0 |
| 1972 | 14303 | 28711 | 8392 | 0 | 107770 | 111141 | 0 |
| 1973 | 3130 | 6282 | 1836 | 0 | 180966 | 176907 | 0 |
| 1974 | 9848 | 37145 | 9328 | 0 | 135874 | 153278 | 0 |
| 1975 | 34937 | 57560 | 19294 | 0 | 190557 | 91935 | 0 |
| 1976 | 17589 | 47468 | 13152 | 0 | 143557 | 118779 | 731 |
| 1977 | 17796 | 40539 | 11267 | 0 | 150491 | 57472 | 0 |
| 1978 | 17095 | 12535 | 4026 | 0 | 68747 | 38180 | 0 |
| 1979 | 9712 | 28808 | 7194 | 0 | 140844 | 62622 | 0 |
| 1980 | 22501 | 72485 | 8493 | 0 | 186648 | 94291 | 0 |
| 1981 | 21596 | 86426 | 6658 | 0 | 174222 | 60668 | 0 |
| 1982 | 18478 | 53592 | 7379 | 0 | 143445 | 77017 | 0 |
| 1983 | 15964 | 30185 | 3292 | 0 | 116592 | 55683 | 731 |
| 1984 | 11474 | 11695 | 2421 | 0 | 98184 | 52813 | 731 |
| 1985 | 15400 | 24499 | 7460 | 0 | 131360 | 79275 | 731 |
| 1986 | 17779 | 45321 | 8296 | 0 | 151275 | 91912 | 609 |
| 1987 | 13714 | 64351 | 11389 | 0 | 192308 | 82401 | 487 |
| 1988 | 19641 | 56381 | 7087 | 0 | 115375 | 74620 | 487 |
| 1989 | 13233 | 34200 | 9053 | 0 | 116375 | 60884 | 487 |
| 1990 | 8736 | 20699 | 3592 | 0 | 71761 | 46053 | 458 |
| 1991 | 1410 | 20055 | 5303 | 0 | 62331 | 42721 | 283 |
| 1992 | 9588 | 13336 | 1325 | 0 | 0 | 0 | 565 |
| 1993 | 3893 | 12037 | 1144 | 0 | 0 | 0 | 717 |
| 1994 | 3303 | 4535 | 802 | 0 | 0 | 0 | 834 |
| 1995 | 3202 | 4561 | 217 | 0 | 0 | 0 | 204 |
| 1996 | 1676 | 5308 | 865 | 0 | 0 | 0 | 382 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1997 | 1728 | 8025 | 332 | 0 | 0 | 0 | 363 |
| 1998 | 0 | 0 | 0 | 2988 | 0 | 0 | 562 |
| 1999 | 0 | 0 | 0 | 2739 | 0 | 0 | 566 |
| 2000 | 0 | 0 | 0 | 5323 | 0 | 0 | 552 |
| 2001 | 0 | 0 | 0 | 4789 | 0 | 0 | 525 |
| 2002 | 0 | 0 | 0 | 5806 | 0 | 0 | 476 |
| 2003 | 0 | 0 | 0 | 6477 | 0 | 0 | 731 |
| 2004 | 0 | 0 | 0 | 8385 | 0 | 0 | 892 |
| 2005 | 0 | 0 | 0 | 10436 | 0 | 0 | 926 |
| 2006 | 0 | 0 | 0 | 10377 | 0 | 0 | 985 |
| 2007 | 0 | 0 | 0 | 9208 | 0 | 0 | 458 |
| 2008 | 0 | 0 | 0 | 9834 | 0 | 0 | 926 |
| 2009 | 0 | 0 | 0 | 7988 | 0 | 0 | 857 |
| 2010 | 0 | 0 | 0 | 9867 | 0 | 0 | 602 |
| 2011 | 0 | 0 | 0 | 11138 | 0 | 0 | 145 |
| 2012 | 0 | 0 | 0 | 9977 | 0 | 0 | 327 |
| 2013 | 0 | 0 | 0 | 7185 | 0 | 0 | 542 |
| 2014 | 0 | 0 | 0 | 8958 | 0 | 0 | 440 |
| 2015 | 0 | 0 | 0 | 8923 | 0 | 0 | 988 |
| 2016 | 0 | 0 | 0 | 7645 | 0 | 0 | 1396 |
| 2017 | 0 | 0 | 0 | 6701 | 0 | 0 | 1045 |
| 2018 | 0 | 0 | 0 | 8780 | 0 | 0 | 382 |
| 2019 | 0 | 0 | 0 | 7062 | 0 | 0 | 391 |
| 2020 | 0 | 0 | 0 | 7607 | 0 | 0 | 382 |
| 2021 | 0 | 0 | 0 | 9377 | | | 449 |
| 2022 | 0 | 0 | 0 | 9130 | | | 336 |

**Table 4.11. Catch (number) and biological characteristics of sampled Atlantic salmon at Faroes, 1971 to 2000.**

| Year | Catch (number salmon) | | Unreported catch of 1SW salmon | | Prop. wild |
|---|---|---|---|---|---|
| | 1SW | MSW | Estimated % | Uncertainty in % unreported | |
| 1971 | 2620 | 105796 | 10 | 5 | 1.0 |
| 1972 | 2754 | 111187 | 10 | 5 | 1.0 |
| 1973 | 3121 | 126012 | 10 | 5 | 1.0 |
| 1974 | 2186 | 88276 | 10 | 5 | 1.0 |
| 1975 | 2798 | 112984 | 10 | 5 | 1.0 |
| 1976 | 1830 | 73900 | 10 | 5 | 1.0 |
| 1977 | 1291 | 52112 | 10 | 5 | 1.0 |
| 1978 | 974 | 39309 | 10 | 5 | 1.0 |
| 1979 | 1736 | 70082 | 10 | 5 | 1.0 |
| 1980 | 4523 | 182616 | 10 | 5 | 1.0 |
| 1981 | 7443 | 300542 | 10 | 5 | 1.0 |
| 1982 | 6859 | 276957 | 10 | 5 | 1.0 |
| 1983 | 15861 | 215349 | 10 | 5 | 1.0 |
| 1984 | 5534 | 138227 | 10 | 5 | 1.0 |
| 1985 | 378 | 158103 | 10 | 5 | 0.9 |
| 1986 | 1979 | 180934 | 10 | 5 | 1.0 |
| 1987 | 90 | 166244 | 10 | 5 | 1.0 |
| 1988 | 8637 | 87629 | 10 | 5 | 0.9 |
| 1989 | 1788 | 121965 | 10 | 5 | 0.8 |
| 1990 | 1989 | 140054 | 10 | 5 | 0.5 |
| 1991 | 943 | 84935 | 10 | 5 | 0.5 |
| 1992 | 68 | 35700 | 10 | 5 | 0.6 |
| 1993 | 6 | 30023 | 10 | 5 | 0.7 |
| 1994 | 15 | 31672 | 10 | 5 | 0.7 |
| 1995 | 18 | 34662 | 10 | 5 | 0.8 |
| 1996 | 101 | 28381 | 10 | 5 | 0.8 |
| 1997 | 0 | 0 | 0 | 0 | 0.0 |
| 1998 | 339 | 1424 | 15 | 5 | 0.8 |

| | | | | | |
|---|---|---|---|---|---|
| 1999 | 0 | 0 | 0 | 0 | 0.0 |
| 2000 | 225 | 1765 | 15 | 5 | 0.8 |

**Table 4.12. Harvests (tons) and biological characteristics of sampled Atlantic salmon at West Greenland, 1971 to 2022. From 1971-1984, the proportion 1SW NAC and NEAC (italics) were assumed to be equal to the 1985-1992 mean values. There was insufficient sampling in 1997 and the mean weight and min and max proportion NAC (italics) were derived from the 1975-1979 estimates. The fishery was suspended in 1993 and 1994 and there were no reported landings or sampling of the harvest. The biological characteristics (italics) for these two years were derived from the 1991- 1995 estimates.**

| Year | West Greenland (t) | | Mean weight (kg) | Estimated prop. NAC (scales) | | Prop. 1SW | | Samples to continent (genetics) | |
|---|---|---|---|---|---|---|---|---|---|
| | Reported | Unreported | | min | max | NAC | NEAC | NAC | NEAC |
| 1971 | 2 689.0 | 0.0 | 3.140 | 0.280 | 0.400 | *0.945* | *0.964* | | |
| 1972 | 2 113.0 | 0.0 | 3.440 | 0.340 | 0.370 | *0.945* | *0.964* | | |
| 1973 | 2 341.0 | 0.0 | 4.180 | 0.390 | 0.590 | *0.945* | *0.964* | | |
| 1974 | 1 917.0 | 0.0 | 3.580 | 0.390 | 0.460 | *0.945* | *0.964* | | |
| 1975 | 2 030.0 | 0.0 | 3.120 | 0.400 | 0.480 | *0.945* | *0.964* | | |
| 1976 | 1 175.0 | 0.0 | 3.040 | 0.380 | 0.480 | *0.945* | *0.964* | | |
| 1977 | 1 420.0 | 0.0 | *3.210* | *0.380* | *0.570* | *0.945* | *0.964* | | |
| 1978 | 984.0 | 0.0 | 3.350 | 0.470 | 0.570 | *0.945* | *0.964* | | |
| 1979 | 1 395.0 | 0.0 | 3.340 | 0.480 | 0.520 | *0.945* | *0.964* | | |
| 1980 | 1 194.0 | 0.0 | 3.220 | 0.450 | 0.510 | *0.945* | *0.964* | | |
| 1981 | 1 264.0 | 0.0 | 3.170 | 0.580 | 0.610 | *0.945* | *0.964* | | |
| 1982 | 1 077.0 | 0.0 | 3.110 | 0.600 | 0.640 | *0.945* | *0.964* | | |
| 1983 | 310.0 | 0.0 | 3.100 | 0.380 | 0.410 | *0.945* | *0.964* | | |
| 1984 | 297.0 | 0.0 | 3.110 | 0.470 | 0.530 | *0.945* | *0.964* | | |
| 1985 | 864.0 | 0.0 | 2.870 | 0.460 | 0.530 | 0.925 | 0.950 | | |
| 1986 | 960.0 | 0.0 | 3.030 | 0.480 | 0.660 | 0.951 | 0.975 | | |
| 1987 | 966.0 | 0.0 | 3.160 | 0.540 | 0.630 | 0.963 | 0.980 | | |
| 1988 | 893.0 | 0.0 | 3.180 | 0.380 | 0.490 | 0.967 | 0.981 | | |
| 1989 | 337.0 | 0.0 | 2.870 | 0.520 | 0.600 | 0.923 | 0.955 | | |
| 1990 | 274.0 | 0.0 | 2.690 | 0.700 | 0.790 | 0.957 | 0.963 | | |
| 1991 | 472.0 | 0.0 | 2.650 | 0.610 | 0.690 | 0.956 | 0.934 | | |
| 1992 | 237.0 | 0.0 | 2.810 | 0.500 | 0.570 | 0.919 | 0.975 | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 0.0 | 12.0 | *2.730* | *0.500* | *0.760* | *0.950* | *0.960* | | | |
| 1994 | 0.0 | 12.0 | *2.730* | *0.500* | *0.760* | *0.950* | *0.960* | | | |
| 1995 | 83.0 | 20.0 | 2.560 | 0.650 | 0.720 | 0.968 | 0.973 | | | |
| 1996 | 92.0 | 20.0 | 2.880 | 0.710 | 0.760 | 0.941 | 0.961 | | | |
| 1997 | 58.0 | 5.0 | 2.710 | 0.750 | 0.840 | 0.982 | 0.993 | | | |
| 1998 | 11.0 | 11.0 | 2.780 | 0.730 | 0.840 | 0.968 | 0.994 | | | |
| 1999 | 19.0 | 12.5 | 3.080 | 0.840 | 0.970 | 0.968 | 1.000 | | | |
| 2000 | 21.0 | 10.0 | 2.570 | | | 0.974 | 1.000 | 344 | 146 | |
| 2001 | 43.0 | 10.0 | 3.000 | 0.670 | 0.710 | 0.982 | 0.978 | | | |
| 2002 | 9.8 | 10.0 | 2.900 | | | 0.973 | 1.000 | 338 | 163 | |
| 2003 | 12.3 | 10.0 | 3.040 | | | 0.967 | 0.989 | 1 212 | 567 | |
| 2004 | 17.2 | 10.0 | 3.180 | | | 0.970 | 0.970 | 1 192 | 447 | |
| 2005 | 17.3 | 10.0 | 3.310 | | | 0.924 | 0.967 | 585 | 182 | |
| 2006 | 23.0 | 10.0 | 3.240 | | | 0.930 | 0.988 | 857 | 326 | |
| 2007 | 24.8 | 10.0 | 2.980 | | | 0.965 | 0.956 | 917 | 206 | |
| 2008 | 28.6 | 10.0 | 3.080 | | | 0.974 | 0.988 | 1 593 | 260 | |
| 2009 | 28.0 | 10.0 | 3.500 | | | 0.934 | 0.894 | 1 483 | 138 | |
| 2010 | 43.1 | 10.0 | 3.420 | | | 0.982 | 0.975 | 991 | 249 | |
| 2011 | 27.4 | 10.0 | 3.400 | | | 0.939 | 0.831 | 888 | 72 | |
| 2012 | 34.6 | 10.0 | 3.440 | | | 0.932 | 0.980 | 1 121 | 252 | |
| 2013 | 47.7 | 10.0 | 3.350 | | | 0.949 | 0.966 | 938 | 211 | |
| 2014 | 70.4 | 10.0 | 3.320 | | | 0.913 | 0.961 | 660 | 260 | |
| 2015 | 60.9 | 10.0 | 3.370 | | | 0.970 | 0.982 | 1 337 | 337 | |
| 2016 | 30.2 | 10.0 | 3.180 | | | 0.935 | 0.955 | 864 | 438 | |
| 2017 | 28.0 | 10.0 | 3.490 | | | 0.925 | 0.931 | 734 | 252 | |
| 2018 | 39.0 | 10.0 | 2.970 | | | 0.974 | 0.974 | 814 | 165 | |
| 2019 | 28.3 | 10.0 | 2.960 | | | 0.959 | 0.979 | 766 | 305 | |
| 2020 | 30.9 | 10.0 | 3.500 | | | 0.923 | 0.971 | 109 | 87 | |
| 2021 | 41.8 | 10.0 | 3.420 | | | 0.955 | 0.979 | 1250 | 268 | |
| 2022 | 29.0 | 10.0 | 2.850 | | | 0.947 | 0.900 | 627 | 42 | |

### 4.3.3 Faroes fisheries catches and splits

The catch in the historical fisheries at Faroes has previously been split into the different NEAC stock-units assuming homogenous harvest rates, after removing a fixed proportion of North American fish. Recent analyses of genetic data (O'Sullivan *et al*., 2022) question this hypothesis. The working group therefore decided to use the available genetic data, which is from an experimental long-line fishery occurring in the 92/93, 93/94 and 94/95 fishing seasons. The genetic assignment (Table 4.13 and Table 4.14) is described in Gilbey *et al*. (2017) and O'Sullivan *et al*. (2022). It is not feasible to use genetic data to inform the split among all stock-units in NEAC, we therefore decided to divide NEAC into three stock complexes: S-NEAC, which includes France, UK – England and Wales, UK – Scotland, UK – Northern Ireland, Ireland and Iceland (SW); N-NEAC (south), which includes Iceland (NE), Sweeden and Norway (SE, SW and MI); and N-NEAC (north), which includes Norway (NO), Finland and Russia. The split of N-NEAC into two groups is not only supported by the analysis of O'Sullivan *et al*. (2022), but also of satellite tagging studies (Rikardsen *et al*., 2021).

**Table 4.13. Distribution (number) of 1SW fish genetic samples for each stock complex across the fishing season. For comparison, the last row shows the monthly historical catch proportions of 1SW fish in the Faroes commercial fisheries in the period 83/84-90/91 (Potter *et al.,* 2015). The monthly number of genetic samples was adjusted according to the distribution of the historical catch to obtain the adjusted distribution of genetic samples across stock complexes (Total adj.).**

| Stock complex | Nov | Dec | Jan | Feb | Mar | Apr-June | Total | Total adj.* |
|---|---|---|---|---|---|---|---|---|
| NAC | 1 | | | 12 | 3 | | 16 (6.3%) | 7.6% |
| S-NEAC | 18 | 39 | | 117 | 14 | | 188 (74.0%) | 76.9% |
| N-NEAC (south) | 2 | 17 | | 11 | 14 | | 44 (17.3%) | 13.2% |
| N-NEAC (north) | | | | 2 | 4 | | 6 (2.4%) | 2.3% |
| Sum | 21 (8.3%) | 56 (22%) | | 142 (55.9%) | 35 (13.8%) | | 254 (100%) | |
| Mean 1SW catch | 117 (2.5%) | 349 (7.4%) | 212 (4.5%) | 3084 (64.9%) | 414 (8.7%) | 573 (12.0%) | 4749 (100%) | |

* The adjustment was performed by scaling the number of genetic samples by % historical monthly catch divided by % monthly genetic samples. For example, the November values were multiplied by 2.5/8.3.

**Table 4.14. Distribution of MSW fish genetic samples for each stock complex across the fishing season. For comparison, the last row shows the monthly historical catch proportions of MSW fish in the Faroes commercial fisheries in the period 83/84-90/91 (Potter *et al.,* 2015). The monthly number of genetic samples was adjusted according to the distribution of the historical catch to obtain the adjusted distribution of genetic samples across stock complexes (Total adj.).**

| Stock complex | Nov | Dec | Jan | Feb | Mar | Apr-June | Total | Total adj.* |
|---|---|---|---|---|---|---|---|---|
| NAC | 58 | 37 | | 33 | 44 | | 172 (9.2%) | 13.0% |
| S-NEAC | 110 | 96 | | 52 | 179 | | 437 (23.3%) | 28.9% |
| N-NEAC (south) | 100 | 114 | | 78 | 663 | | 955 (50.8%) | 46.3% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| N-NEAC (north) | 8 | 18 | | 18 | 270 | | 314 (16.7%) | 11.8% |
| Sum | 276 (14.7%) | 264 (14.1%) | | 181 (9.6%) | 1156 (61.6%) | | 1878 (100%) | |
| Mean MSW catch | 7671 (6.6%) | 27809 (24.0%) | 8719 (7.5%) | 20147 (17.4%) | 21185 (18.3%) | 30283 (26.2%) | 115814 (100%) | |

* The adjustment was performed by scaling the number of genetic samples by % historical monthly catch divided by % monthly genetic samples. For example, the December values were multiplied by 24.0/14.1.

**NAC-NEAC split**

The adjusted percentage of North American fish in the genetic samples (Table 4.13 and Table 4.14) provide updated values for the fixed proportion of NAC fish that should be removed prior to splitting the Faroes catch among the NEAC stock-units. The new values of 7.6% 1SW and 13.0% MSW NAC fish in the Faroes fishery differ from the old values of 5.7% 1SW and 20.5% MSW fish, respectively.

**NEAC split**

Instead of using homogenous harvest rates, we inform the split between S-NEAC, N-NEAC (south) and N-NEAC (north) using a combination of genetic data and changes in abundance. Within these different three stock complexes we do not have sufficient resolution of the genetic data to perform a genetically informed split. Hence, we rely on the homogenous harvest rate hypothesis at this lower level.

To achieve a genetically informed split, we use a genetically informed relative harvest rate for each stock complex. We calculated the catch for stock complex *i* in year *t* by

$$C_{it} = h_t \alpha_{it} N_{it}$$

where $h_t$ is the total harvest rate, $\alpha_{it}$ is the genetically informed relative harvest rate and $N_{it}$ is the abundance. Using the fact that the total harvest rate is given by $h_t = \sum_i C_{it} / \sum_i N_{it}$ and rearranging the above equation, we have that the genetically informed harvest rate for a focal stock complex $i$ = A is

$$\alpha_{At} = P_{At} \frac{\sum_i N_{it}}{N_{At}}$$

where $P_{At} = C_{At} / \sum_i C_{it}$ is the proportion of the fish from the focal stock complex in the catch.

Because we have an estimate of the proportion of fish in the catch from each stock complex from the genetic data ($P_{\text{genetic}}$) and historical pre-fishery abundance (PFA) estimates from the same period, we can estimate the average relative harvest rates $\bar{\boldsymbol{\alpha}}$ for this period (Table 4.15 and Table 4.16). The estimates of $\bar{\alpha}$ clearly show that the S-NEAC 1SW fish and the N-NEAC (south) MSW fish were overrepresented in the catch at Faroes. The fish from N-NEAC (north) were underrepresented in the catch at Faroes and more so for 1SW compared to MSW fish. This is not surprising, as N-NEAC (north) fish migrate both eastward into the Barents Sea and westward int the Norwegian sea (Rikardsen *et al.,* 2021). In addition, the 1SW fish presumably have shorter migration routes compared to MSW fish. The genetically informed harvest rates approach differs substantially from the previously used homogenous harvest rate approach (Figure 4.2).

**Table 4.15. 1SW fish: adjusted proportions of the different stock complexes in the genetic data ($P_{genetic}$), the average PFA of the different stock complexes in the period 1993-1995 and corresponding values of average relative harvest rates ($\bar{\alpha}$).**

| Stock complex | $P_{genetic}$* | $\overline{PFA}$ | $\bar{\alpha}$ (95% CI) |
|---|---|---|---|
| S-NEAC | 83.2% | 2 355 573 (60.8%) | 1.37 (1.28-1.47) |
| N-NEAC (south) | 14.3% | 731 332 (18.9%) | 0.76 (0.52-1.01) |
| N-NEAC (north) | 2.5% | 789 100 (20.3%) | 0.12 (0.04-0.23) |
| Sum | 100% | 3 876 004 (100%) | |

* These values are based on the “Total adj.” in Table 4.13.

**Table 4.16. MSW fish: adjusted proportions of the different stock complexes in the genetic data ($P_{genetic}$), the average PFA of the different stock complexes in the period 1993-1995 and corresponding values of average relative harvest rates ($\bar{\alpha}$).**

| Stock complex | $P_{genetic}$* | $\overline{PFA}$ | $\bar{\alpha}$ (95% CI) |
|---|---|---|---|
| S-NEAC | 33.2% | 458 249 (47.1%) | 0.71 (0.63-0.79) |
| N-NEAC (south) | 53.2% | 210 810 (21.6%) | 2.46 (2.20-2.76) |
| N-NEAC (north) | 13.6% | 304 719 (31.3%) | 0.43 (0.37-0.50) |
| Sum | 100% | 973 778 (100%) | |

* These values are based on the “Total adj.” in and Table 4.14.


**Figure 4.2. Harvest rates for the three stock complexes using the genetically informed approach (Genetic) vs the homogenous harvest rate approach (Homogenous) for 1SW and MSW fish.**

To estimate the uncertainty in $\alpha$ we used parametric bootstrap on the genetic data sampling from a multinomial distribution according to the adjusted proportions in the genetic data and the total sample size. We combined this distribution with the Monte Carlo distribution of PFA values from the run-reconstruction model. The relative harvest rates had higher uncertainty for the 1SW fish (Table 4.15) compared to the MSW fish (Table 4.16), as we would expect from the sample sizes in the genetic data. The uncertainty distributions of the $\alpha$ values were very close to multivariate normal (Figure 4.2 and Figure 4.3), except for 1SW fish in N-NEAC (north) that were truncated at zero. Hence, we can take the uncertainty into account by sampling values from a multivariate normal distribution using the mean and (co)variances in Table 4.17 and truncate the values at zero (it is not possible to have a negative harvest rate).

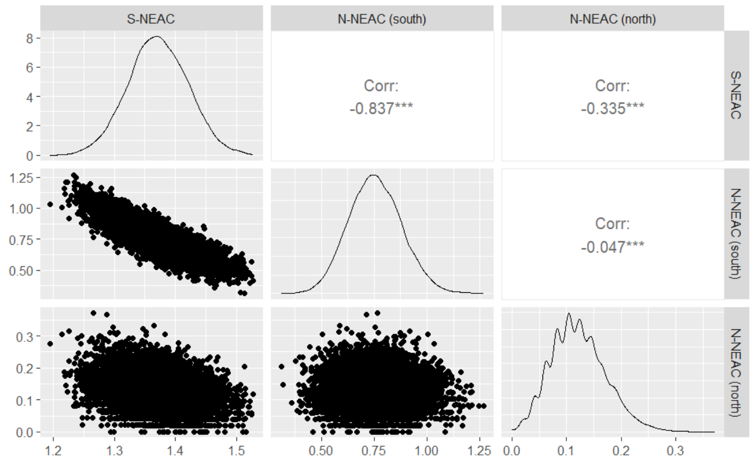


**Figure 4.3. Multivariate uncertainty distribution of $\alpha$ values for 1SW fish based on 9999 draws from Monte Carlo sampling of PFA values from the run-reconstruction model and parametric bootstrap of the genetic data.**

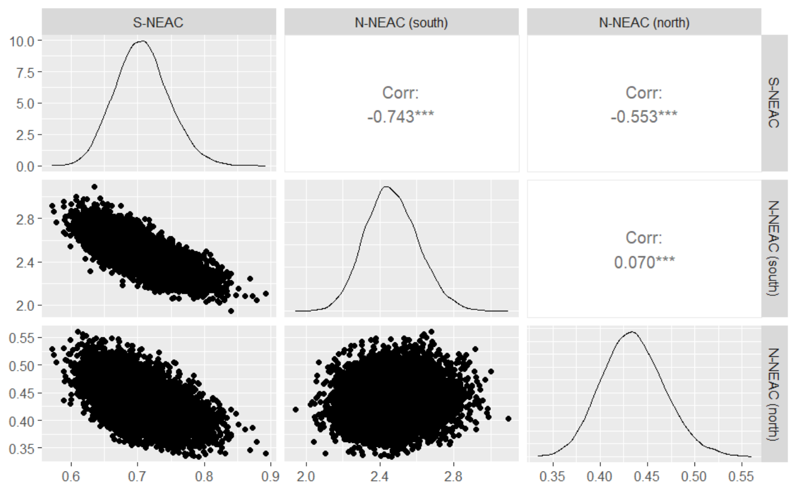


**Figure 4.4. Multivariate uncertainty distribution of $\alpha$ values for MSW fish based on 9999 draws from Monte Carlo sampling of PFA values from the run-reconstruction model and parametric bootstrap of the genetic data.**

**Table 4.17. Means and variance matrix for the uncertainty distributions of the $\alpha$ values shown in Figure 4.3. and Figure 4.4.**

| Stock complex | Means | Variance matrix (x100) | | |
|---|---|---|---|---|
| 1SW: | | | | |
| S-NEAC | 1.371 | 0.238 | -0.508 | -0.082 |
| N-NEAC (south) | 0.755 | | 1.549 | -0.029 |
| N-NEAC (north) | 0.122 | | | 0.250 |
| MSW: | | | | |
| S-NEAC | 0.706 | 0.163 | -0.428 | -0.074 |
| N-NEAC (south) | 2.466 | | 2.038 | 0.033 |
| N-NEAC (north) | 0.435 | | | 0.109 |

To ensure that the total harvest does not exceed its actual value due to rounding errors and/or sampling the $\alpha$ values from an uncertainty distribution approximated by a multivariate normal, we use the fact that $\sum_i \alpha_i h_t N_{it}$ should equal $\sum_i h_t N_{it}$ and scale the distribution of $\alpha$ values accordingly:

$$\alpha_{At}^{*} = \alpha_{At} \frac{\sum_i N_{it}}{\sum_i \alpha_i N_{it}},$$

where $\alpha_{At}^{*}$ are the scaled values for the focal stock complex $i = A$ in year $t$. Note that in this equation, all parameters are random in the sense that they have a distribution.

### 4.3.4 West Greenland fisheries catches and splits

West Greenland fishery is assumed to harvest primarily the 1SW non-maturing component of the populations. Catches at West Greenland may originate from any of the 25 stock-units from all Continental Stock Groups (CSG). Total catches are allocated to the different stock-units following a three level allocation rule:

- **Level 1.** First, total catches are allocated to the North American (NAC) or European (NEAC) complexes using proportions calculated from a compilation of individual assignment data based on discriminant analyses of scale characteristics or genetic analyses (Table 4.12).
- **Level 2**. Second, within the European stock complex, catches are allocated to the Southern or Northern European CSG using proportions calculated from genetic-based mixture analysis or individual assignments.
- **Level 3**. Within each of the three different stock complexes we do not have sufficient resolution of the genetic data to perform a genetically informed split at this time. Hence, we rely on the homogenous harvest rate hypothesis at this lower level (within each of the three complexes)

*NAC–NEAC split (level 1)*

The catch at West Greenland was divided into NAC and NEAC components using scale characteristics from 1971-2001 (excluding 2000) and genetic analysis from 2000-2022 (exclusing 2001).

From 1969–2001 (excluding 2000), scale pattern analysis was used to make continent of origin determinations and estimate the proportion of the harvest originating in North American and European rivers. The technique had proven to be a reliable method for discriminating and identifying salmon caught to the continent of origin (Lear and Sandeman 1980; Reddin 1986; Reddin *et al.*, 1988; Reddin *et al.*, 1990; Reddin and Friedand 1999). The method of Pella and Robertson (1979) was used to correct for misclassifications. From 2000–2016 (excluding 2001), DNA isolation and the subsequent microsatellite analyses were performed according to standardized protocols to assign samples to continent of origin with very high reliability (100%) (King *et al.*, 1999, 2001; Sheehan *et al.*, 2010). A database of approximately 5000 Atlantic salmon genotypes of known origin were used as a baseline to assign the samples to continent of origin. Since 2017, a Single Nucleotide Polymorphism (SNP) range-wide baseline (Jeffery *et al.*, 2018) providing 20 North American and eight European reporting groups has been used for continent and region of origin analysis. A revised baseline distinguishes 21 North American and ten European reporting groups (Bradbury *et al.*, 2021). A Bayesian approach in the R package rubias (Anderson *et al.*, 2008) is used to assign individuals to continent of origin.

For the period when scale characteristics were used, the input data to the model are the minimum and maximum estimates of the proportion of NAC fish (from which minimum and maximum proportions of NEAC fish are calculated). For the subsequent period when genetic assignments were used, the inputs are the numbers of NAC and NEAC fish identified in the samples. The time series of assigned proportions of NAC and NEAC salmon using scale discriminant analysis and samples assigned to NAC and NEAC are shown in Table 4.12. The time series extends from 1971 to 2022.

*Southern NEAC / Northern NEAC split (level 2)*

Instead of using homogenous harvest rates, we inform the split between S-NEAC and N-NEAC using a combination of genetic data and changes in relative abundance.

Genetic data were available from two sources:

1. SNP –based mixture analysis for the years 1983–1984, 1996–1998 and 2017–2022

SNP –based mixture analysis data represent a re-analysis of previously reported data (Bradbury *et al.*, 2016; Jeffery *et al.*, 2018; Bradbury *et al.*, 2021) with the incorporation of previous unreported data against the revised baseline. Sample size was approximately 100–1500 samples per year and typically originated from one NAFO Division in the early part of the time series and multiple NAFO Divisions in the later. A Bayesian approach in the R package rubias (Anderson *et al.*, 2008) was used to conduct the mixture analysis as outlined Bradbury *et al.* (2021).

Post-analysis processing of the data was required. Given the nature of the mixture assignment process, very small assignment probabilities (mean < 0.0004%) are provided for stocks that are not relevant to the LCM approach, but are included within the baseline (i.e. aquaculture and Baltic origin salmon). In addition, small probabilities of Greenland origin salmon were also removed (2 individual fish from the samples have been identified as originating from the Kapisillit River, Greenland’s only native Atlantic salmon population, since 2017), as the LCM model does not currently consider Greenland origin salmon. The probability associated with the Iceland stock grouping was split in half and allocated to the S- and N-NEAC equally. Finally, S- and N-NEAC probabilities were scaled to 1.

2. Microsatellite-based individual assignments for the years 2002 and 2004–2012

Microsatelite-based individual assignments were performed against the "GRAASP: Genetically-based Regional Assignment of Atlantic Salmon Protocol" SALSEA Regional Assignment Units (SRAUs) Level 1 (IASRB 2014; Gilbey *et al.,* 2018). The analysis was performed on all European origin individuals previously identified within the Level 1 processing. Sample size ranged from 56-408 individuals from multiple NAFO Divisions per year. Fish assigned to the Iceland assignment unit were equally distributed between S and N-NEAC. The proportion of sampled fish from S- and N-NEAC were calculated from the sum of the individual assignments. The results from the Level 2 assignment are shown in Figure 4.5.

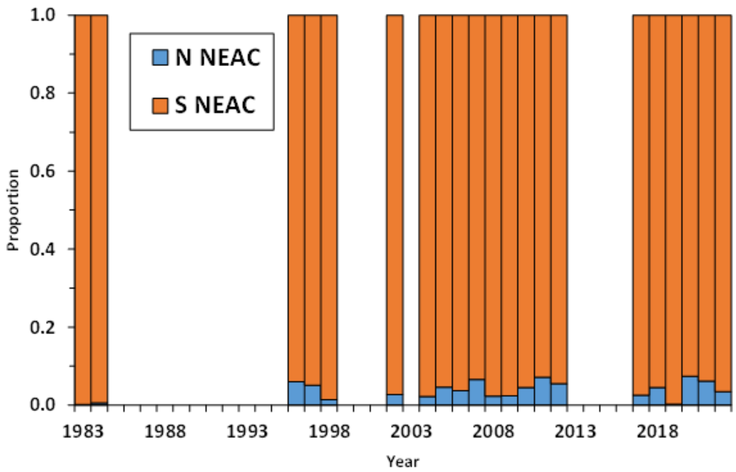


**Figure 4.5. Estimate proportion of S- and N-NEAC fish in the European harvest at West Greenland. Estimated proportions are based SNP-based mixture analysis for the years 1983–1984, 1996–1998 and 2017–2022 and microsatelite-based individual assignments for 2002 and 2003–2012.**

Estimates of proportion of fish in the catches from each stock complex are available from the genetic data and historical PFA estimates (non-maturing PFA) from the same period. We estimate the relative harvest rate using a similar method than the one described for Faroes catch split. Estimates of the relative harvest rate for each year where genetic data were available clearly show that the S-NEAC non-maturing 1SW fish were overrepresented in the catch at West Greenland with regards to the Northern NEAC fish (Figure 4.6; Table 4.17). This is not surprising as stocks from Northern NEAC do not contribute a significant amount to the harvest at West Greenland (ICES, 2023).

The average relative harvest rate calculated based on years for which genetic data are available was then combined with the relative proportion in the non-maturing PFA to predict what could be the genetic proportion in the catches for years where genetic data are missing (Figure 4.7).

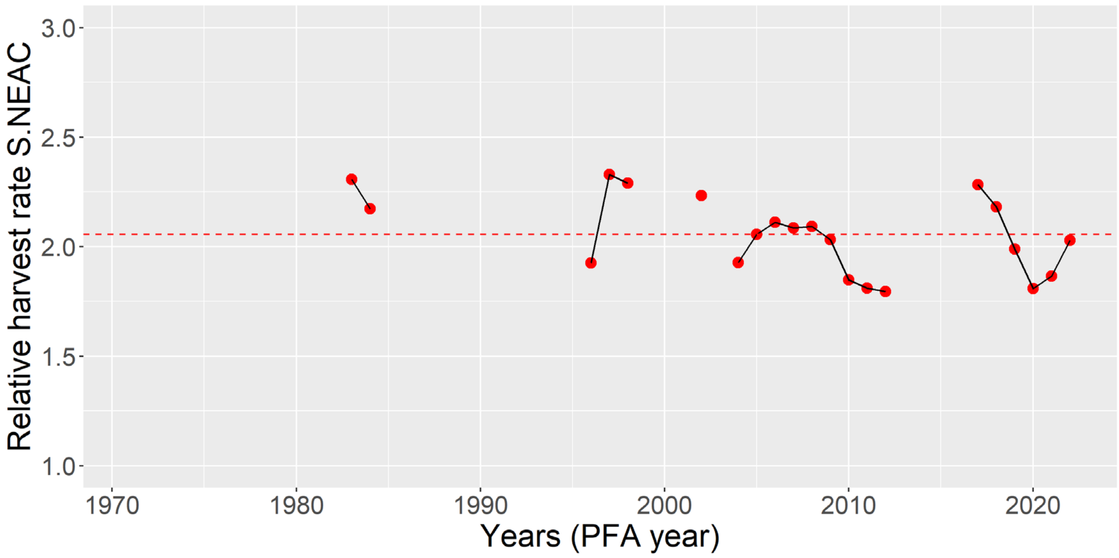


**Figure 4.6. Relative harvest rates of fish from Southern NEAC (relative to fish originated from Northern NEAC) in the West Greenland 1SW non-maturing fishery, estimated for years (PFA years) when genetic data are available. The red dashed line is the average relative harvest rate used to predict the genetic proportion for years when no data are available.**

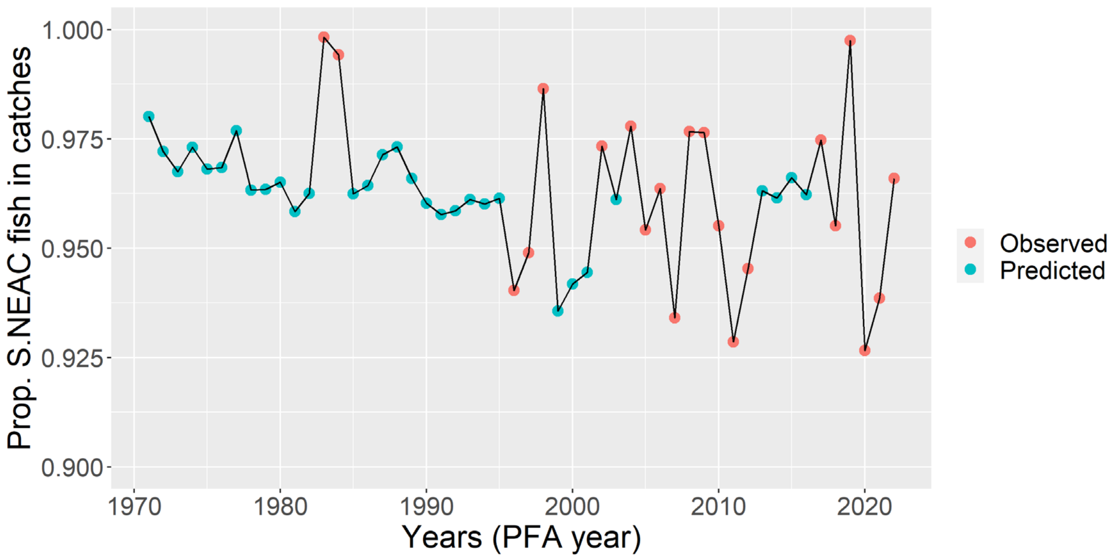


**Figure 4.7. Proportion of fish originated from Southern NEAC in the West Greenland catches of NEAC origin salmon. "Observed proportions" are directly inferred from genetic assignment. Predicted proportions are inferred from the relative harvest rate method.**

## 4.4 New Stock-units

Consideration was given to the inclusion of Danish time series of salmon data. These being in 2009. Considering the 1971 starting point for other stock-units in S-NEAC and issues to be resolved aligning data they were not implemented at this stage. It is intended that Danish expert members within the WGNAS will continue to coordinate data formats and datastreams for a Danish stock-unit appropriate to the Run Reconstruction and LCM to be implement in the near future. Salmon stock-units relating to Germany, The Netherlands, Spain and Portugal were also considered during the June

WKBSalmon meeting, however, they have not yet been fully compiled by national laboratories and are not consistent for inclusion.

# 5 Life Cycle Model

## 5.1 Background

ICES WGNAS has developed stock assessment models for Atlantic salmon based on data aggregated at the scale of regional or national stock-units over the North Atlantic area within three Continental Stock Groups (CSG): eastern North America (NAC), Southern European (S-NEAC) and Northern European (N-NEAC).

These models were designed to reconstruct long term timeseries (starting in the early 1970’s) of annual abundance at sea, estimating population sizes before any marine fisheries take place, “pre-fisheries abundance” (PFA) and to forecast the returns of adult salmon to their natal rivers (homewaters) over three years following the assessment year. These models (hereafter denoted PFA models) were incorporated in a risk analysis framework to assess the consequences of mixed salmon stock marine fisheries, at West Greenland and the Faroes, on the homewater returns and to assess the compliance of realized spawning escapement (the number of salmon arriving back to a management unit) to spawn, to conservation limits (biological references point below which the stock should not pass) at the CSG scales and at the stock-unit scale.

Limitations of the PFA modelling framework had been identified and a new Life Cycle Modelling framework (LCM) for the stock assessment of Atlantic salmon in the North Atlantic basin was developed and proposed to i) enhance assessment methodology and workflow from data specification, preparation and maintenance to the production of the assessment and for provision of multi-year forecasts and catch advice and; ii) improve the biological realism of the stock assessment model.

## 5.2 A new stock assessment framework

The new stock assessment framework offers three main axes of improvement.

- First, PFA models used to date for formulating catch advice rely on a coarsely constructed stock-recruitment dynamic. Forecasts of the returns during the three years following the most recent data/assessment rely on the prediction of the recruitment (as measured as the abundance at the PFA stage) given the stock (expressed as a number of eggs potentially spawned each year for the two European CSG or as the potential number of spawners in the North American CSG). This framework does not explicitly represent the population dynamics as a life cycle. Statistical inferences on the time series of productivity parameters are susceptible to time series bias because the dynamic link between PFA (the measure of recruitment) and subsequent egg depositions (measure of stock) is not represented (Massiot-Granier *et al.*, 2014). The lack of flexibility in the statistical modelling framework also restricts the integration of the large amount of data and knowledge on Atlantic salmon demographics and population dynamics. As such, hypotheses on drivers and mechanisms of changes cannot be easily tested (Massiot-Granier *et al.*, 2014; Olmos *et al.*, 2019).
- Second, the PFA modelling workflow operates as a combination of three models, making standardization of input data and outputs more complex owing to subtle differences in assumptions and derivations:
    - o Run reconstructions relies on estimates of the abundance of fish returning to spawn and biological parameters (sex ratio, fecundity and mean proportions of smolts at

various ages) (inputs) to estimate the potential number of spawners or eggs (measure of the Stock) for each year of the time series (outputs).

  - This produces estimates of the Stock size and Recruitment size, derived within each Run Reconstruction from data entered, whilst they are considered independent (within each Run Reconstruction) for the rest of the Run Reconstruction process.
  - The workflow then consists of estimating the productivity parameters between the Stock and Recruitment for all years of the historical time series and uses time series modelling (random walk) to forecast the evolution of the productivity parameter forward three years beyond the most recent assessment/data-observation year.
  - Productivity parameters and estimates of lagged spawners for the forecast years serve as the basis for producing probability profiling for a range of catch scenarios, derived using the forecast PFAs and numbers of fish returning to homewaters, following a range of scenarios of catches at sea.

- Third, three different and independent PFA models were developed for the three CSG. Some core demographic hypotheses are not harmonized among these models. Specifically, the two European models explicitly consider 1SW and MSW fish in the population dynamics, while the current model for North-America, which was developed for catch advice purposes at West Greenland, only considers the dynamics of 2SW fish (Chaput, 2012) with no comparable consideration of 1SW salmon sea productivity as expressed in the European CSGs. The North-America model also implicitly assumes that 2SW spawners only produce 2SW fish in future cohorts and therefore excludes contributions of 1SW and any fish older than 2SW. The underlying rationale for this simplification is that 1SW non-maturing, potentially 2SW salmon returns, comprise the vast majority of North-American salmon caught at West Greenland. Because of these differences, the commonality in temporal trends between all stock-units in the North Atlantic could not be evaluated with the existing PFA estimation method. This approach also ignores any covariance structure in the dynamics of the stock-units for NEAC, although for the NAC the stock unit productivity parameters are modelled with a multi-normal distribution, even though salmon represented in each may share common environments at sea and be jointly exploited in sea fisheries. This precludes evaluation of the consequences of scenarios on multiple stock complexes simultaneously – both mixed stock fisheries and environmental factors.
- Further multiple PFA models requires duplication of common data feeds and processing of results that could be better managed within a single framework.

The new LCM bring improvements to the scientific basis for Atlantic salmon stock assessment (Table 5.1):

- In the LCM, the dynamics of all stock-units in Northern Europe, Southern Europe and North America (25 stock-units) are considered within a single unified model where all stock-units follow a similar life history process. The new life cycle model provides a singular harmonized framework to simultaneously assess two sea-age classes of Atlantic salmon for all stock-units in North America and Europe and hence allows for analyzing the commonality in the population dynamics among the 25 stock-units of the North Atlantic basin.
- The LCM constitutes an important tool for future improvement of our understanding of the mechanisms driving the response of Atlantic salmon populations to variations in biological and environmental factors in a hierarchy of spatial scales. Formulating the dynamics of all stock-units in a single hierarchical model provides a tool for modelling covariations among different populations that may share part of their migration routes at sea and may be exploited by the same marine fisheries. It is a framework for quantifying the spatial coherence in the temporal variations of post-smolt survival and

of the sea-age composition of returns for stock-units distributed across a broad gradient of longitude and latitude in the North Atlantic basin as a response to global scale environmental changes in the North Atlantic basin.

- The model provides estimates of marine survival from smolts to PFA stages and of the probability to mature as 1SW for the 25 stock-units for more than 50 years (since 1971). Results exhibit clear temporal signals and strong covariations among the 25 stock-units. The smolt-to-PFA survival rates exhibit an overall decreasing trend, with the survival declining by an estimated 67% over 50 years. The probability of salmon maturing as 1SW salmon first increases (which means a decline in the proportion of MSW fish in the returns) in the early part of the timeseries, but then reaches a plateau (especially for European fish) since the late 1990's. The shared signal between the stock-units explains about 40% of the modelled variability in stock-unit maturation, with covariation that increases with the spatial proximity of the migration routes, which is fairly consistent with a response of populations to some large-scale synchronizing factors (Olmos et al., 2020).
- Results of the LCM can be used to quantify the amount of temporal variation in key life history traits that is accounted for by changes in Sea Surface Temperature (SST) and primary productivity (Olmos et al., 2020). As a proof of concept, Olmos et al. (2020) explored if time variations of survival correlate with proxies of environmental/trophic conditions integrated over foraging habitats occupied by multiple populations during the late summer/fall, around the Norwegian sea for European populations and around Labrador Sea for North American populations. The authors found that time variations in survival were significantly negatively correlated with time variations in SST and significantly positively correlated with time variations in primary productivity. These results re-enforce the hypothesis of the response of populations to large scale environmental changes. The LCM framework provides a tool to further test these hypotheses in the future and explore the opportunity to propose improvements in stock assessment and advice through integration of environmental covariates.
- The integrated life cycle framework is expandable and provides an opportunity to assimilate new sources of data to make the best use of all available biological and ecological information. For instance,
    - it incorporates the possibility to provide time series of biological characteristics data to capture any potential trends (for instance, any trend in the average fecundity of females that would result from a trend in body size).
    - it incorporates likelihood functions to better consider uncertainty in the data. For instance, the likelihood component of the LCM includes time series estimates (approximated as log-normal distributions) of homewater catches for each stock-unit by sea-age class, and mixed-stock catches (West Greenland and Faroes) operating sequentially on combinations of stock-units and using additional data on the stock-unit origin of the catches.
- It includes terms to assimilate genetic data to allocate mixed stock fisheries to the different stock complex. A two-stage likelihood function is used to allocate catches at West Greenland; first between the North American and European stock complexes and then between the Northern and Southern European Stock complexes. The structure is flexible and could be enhanced. As a proof of concept, another version of the model developed by Olmos et al. (2019) demonstrated the possibility of including a new likelihood function to assimilate genetic data to allocate catches at West Greenland among all the individual stock-units in NAC and NEAC. Provided that the genetic data are reliable, this would provide a valuable option to make the best use of the available data.

**Table 5.1. Weaknesses of the currently used stock assessment (PFA models) and proposed improvements through the hierarchical life cycle model.**

| | PFA models | Improvement through the life cycle model |
|---|---|---|
| A coarsely constructed stock-recruitment dynamic | Forecasts of the returns are based on forecasts of productivity between a spawning potential and abundance at the PFA stage (measure of the recruitment).<br>The dynamic link between PFA and subsequent egg depositions is not represented; so statistical inferences on productivity is susceptible to time series bias.<br>Lack of flexibility in the statistical modelling framework restricts the integration of the large amount of available data and knowledge. | A life cycle to represent all stages and life histories.<br>This integrated life cycle framework is expandable.<br>Can assimilate new sources of information to improve the ecological and biological realism of the model. |
| Measure of the stock and the recruitment are derived from the same data | A tricky combination of three modeling steps.<br>The same model is used to estimate the abundance of fish at the PFA stages (recruitment) and to estimate the potential number of spawners or eggs (stock).<br>A model to forecast the evolution of the productivity parameter.<br>The forecast model serves as a basis to forecast the PFA and the number of fish that return to homewater based on catch scenarios at sea. | Outputs for returns and catches from run reconstruction are the starting inputs for the LCM.<br>The same model is used for both the inferences hindcasting and forecasting phases.<br>All the model properties and sources of uncertainties are readily integrated into the forecast process. |
| Three different and independent PFA models for each complex with different life histories modelled | The two European models explicitly consider 1SW and MSW fish in the population dynamics.<br>The model for NAC only considers the dynamics of 2SW which implicitly assumes that only 2SW spawners produce 2SW fish in future cohorts and excludes contributions of 1SW and other sea-age groups.<br>Temporal variations of productivities are therefore not comparable to the PFA models built for the European CSG which consider both 1SW and MSW productivity.<br>Cannot evaluate the commonality in temporal trends between all stock-units in the North Atlantic.<br>Ignores any covariance structure in the dynamics of the stock-units between NAC and NEAC (with this precision required in the NAC PFA model as the productivity parameter is defined in a mulit-normal distribution for the six stock-units). Ignoring covariance structure that:<br>▪ may share common environments at sea and<br>▪ are exploited in sea fisheries<br>Precludes evaluation of the consequences of scenarios on multiple stock complexes simultaneously.<br>Hypotheses on drivers and mechanisms of changes cannot be easily tested. | A single unified life cycle approach with all populations following a similar life history process.<br>A framework to enhance the ecosystem approach. This framework analyses the mechanisms that shape population responses to variations in marine ecosystems<br>▪ by modelling covariations among all stock-units<br>▪ by partitioning the effects of fisheries from the effects of environmental factors<br>Evaluate catch options for the Faroes and West Greenland separately or simultaneously and for all stock-units separately or simultaneously. |

## 5.3 Bayesian life cycle model

The core of the new modelling framework is a Bayesian hierarchical life cycle model which tracks the abundance of fish through time and life stages from eggs to adults that return to spawn in their homewater after one or two winters spent at sea and for stock-units in Northern Europe, Southern Europe and North America (see Figure 3.1 and Rivot *et al.*, 2023 for a detailed description of the model).

The life cycle model is a stage-based population model formulated in a Bayesian hierarchical state-space framework that incorporates stochasticity in population dynamics as well as observation errors.

### 5.3.1 LCM spatial structure

The model considers the dynamics of 25 stock-units, defined on the basis of jurisdictional boundaries where salmon abundance as returns and catches are quantified (Sections 3 and 4). All salmon within a stock-unit are assumed to have the same demographic parameters and to undertake a similar migration route at sea. The assessment assumes no exchange of abundance in homewaters among the different stock-units (straying behaviour). The population dynamics are not however, independent among stock-units as the model includes the possibility of covariations in the temporally varying key transition rates (e.g. marine survival and the proportion of fish that mature as 1SW; see more details hereafter) to represent the effect of external factors that might influence multiple populations simultaneously.

### 5.3.2 Stage structure and variability of life histories

The population dynamics of each of the 25 stock-units is represented by an age- and stage-structured life cycle model (Figure 5.1). The model is built in discrete annual time-steps. It tracks the abundance of fish, males and females confounded for each stock-unit by year and life stage, sequentially from eggs to 1SW or MSW spawners for the period considered (starting in 1971, the year of return to rivers). Spawners are fish that contribute to reproduction and therefore those that survived all sources of natural and fishing mortality.

For each stock-unit, the model incorporates expected variations in the age of out-migrating juveniles from freshwater (i.e., smolt ages) and the sea-age of returning adults. Smolts migrate to sea after 1 to 6 years in freshwater (with variations among stock-units). An important model condition is that there is no tracking of smolt-age once at sea, meaning that all transition rates applied to post-smolts at sea only depend on the migration year and are independent of the smolt age.

Following the approach used by ICES for catch advice purposes, only two sea-age classes are considered: maiden salmon that return to homewaters to spawn after one year at sea, referred to as one-sea-winter (1SW) salmon, or grilse and maiden salmon that return after two or more winters at sea (multi-sea-winter; MSW). This is a simplification of the larger diversity of life history traits as some maiden fish may spend more than two winters at sea before returning to spawn and some salmon return as repeat spawners. However, the six smolt-ages combined with the maiden 1SW and MSW spawners (12 potential combinations total) already represent the essence of life history variation in North America and Europe. Also note that not all combinations really exist for all stock-units as the smolt-ages are generally concentrated on 2 or 3 ages in each stock-unit (for instance, mostly age-1 and age-2 smolts in France; versus mostly age-4 and age-5 in Labrador).

The model is not structured by sex. The abundance at each life-stage represents both sexes confounded. The proportion of females is only used to calculate the egg deposition based on the spawner abundances and biological characteristics (separately for the two sea-age classes).

Another fundamental model condition and difference from the run reconstruction model for the NAC is that there is no heritability in the life histories. In particular, 1SW and MSW spawners contribute to a single pool of eggs each year with all eggs considered equivalent, independent of the spawners life history.

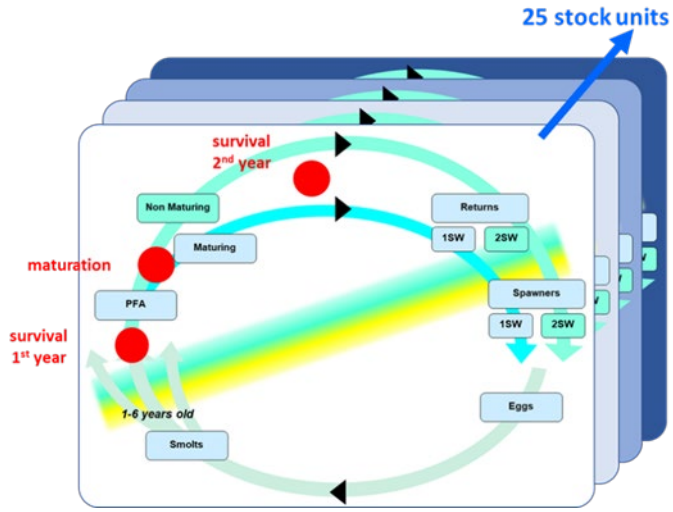


**Figure 5.1. Scheme of the stage-based structured life cycle model. for the 25 stock-units. Blue boxes: different life stages. For each stock-unit, the model tracks the abundance of fish, males and females confounded by year and life stage, sequentially from eggs to 1SW or MSW spawners (fish that survived all sources of natural and fishing mortality and that contribute to reproduction). The model incorporates variations in the age of out-migrating smolts (after 1 to 6 years in freshwater) and the sea-age of returning adults. Only two sea-age classes are considered: maiden salmon that return to homewaters to spawn after one year at sea (1SW) and maiden salmon that return after two winters at sea (MSW). All fish within a stock-unit are assumed to have the same demographic parameters and to undertake a similar migration route at sea. There is no exchange of abundance among the different stock-units. Red dots indicate the key demographic transition rates that are the main target of the statistical estimation: survival between smolt and PFA stage, the proportion of fish maturing at the PFA stage (fish that will return as maiden 1SW fish) and the survival during the second year at sea. Mortality during the second year at sea results from the combination of natural mortality (fixed) and fishing mortality (estimated).**

## 5.3.3 Hypotheses to help partition the sources of temporal variability when estimating transition rates

As recognized by the data constraints already expressed in the existing PFA models and discussed by Chaput (2012), Massiot-Granier *et al.* (2014) and Olmos *et al.* (2019), the quality and information provided by the data are limited, which restricts the number of transition rates that can be estimated.

The framework is primarily designed to provide estimates of:

i. abundance at various stages along the life cycle
ii. exploitation rates of all fisheries
iii. post-smolt marine survival rates from out-migrating smolts to the PFA stage
iv. proportion of fish that mature at the PFA stage.

To partition the temporal variability in the natural and fishing mortalities during the freshwater and marine phases and in the proportion of fish that mature at the PFA stage, we use the framework described by Massiot-Granier *et al.* (2014) and Olmos *et al.* (2019):

- The survival rate from eggs to smolts is stochastic among years (lognormal) but with average value and variance fixed and homogeneous among all stock-units. Lognormal stochastic variations are independent across time (no temporal autocorrelation) and across stock-units (no spatial covariation).
- The allocation of the total number of smolts in a cohort to different smolt-ages is deterministic using fixed (provided in the data) proportions of smolt ages.
- Temporal variability of the transition rates of the marine phase only occurs between smolt migration and the PFA stage (defined as abundance of post-smolts at January 1 of the first winter at sea). This transition is decomposed in two steps: natural survival rate from smolt to the PFA stage (estimated) and the proportion of fish that mature at the PFA stage (estimated). After the PFA stage, all transition rates result from the combination of the fishing and natural mortality. The natural mortality (mortality rate per month) after the PFA stages is fixed and homogenous among all stock-units. The fishing mortality rates are estimated and can vary over time.

The model explicitly incorporates temporal covariation among all stock-units in the post-smolt survival and the proportion of fish maturing as 1SW, both modelled as multivariate random walks in the logit scale which captures spatial covariation associated with environmental stochasticity.

### 5.3.4 Data flow

Two different streams are used to integrate data in the modeling approach: i) some data are directly integrated as fixed values; ii) data are integrated through likelihood function to integrate observation errors (the observation process).

*Important note on the sea-age classes*

Importantly, the population dynamics model considers only maiden 1SW and maiden 2SW fish. Other life histories exist such as 3SW and repeat spawners (consecutive and alternate years) that are not explicitly represented in the dynamics. However, the data used for 2SW fish (returns, homewater catches, biological characteristics) actually concern all fish older than maiden 1SW fish, being considered a "plus group" or Multi-sea-winter (MSW) fish. A limitation of the present approach is therefore a mismatch between the way the population dynamics is represented and the data used to inform what is considered in the model as the 2SW component. Future development of the model should consider options to better align the population dynamics hypotheses with the data (e.g., expanding the model to include other life histories).

*Data integrated as fixed values:*

The model integrates data in the form of fixed parameter values:

- The average value and the coefficient of variance (CV) of the eggs-to-smolt survival rate, are fixed at 0.7% and 0.4, respectively;
- The proportions at smolt-age (between 1 and 6) are specific to each stock-unit and may vary among years within a stock unit;
- The natural mortality rate at sea (after the PFA stage) is fixed to M=0.03·month^(-1) (ICES 2004);
- The duration (in months) of the different periods separating the sequential fisheries at sea. These are used to calculate the natural mortality loss during the different periods at sea. They are fixed over time (no variation among years) but may vary among stock-units;

- Additional mortality rates between returns and spawners. They are specific to each stock-unit and may vary in time (so far, 0 for all stock-units except Scotland West and East);
- The proportion of delayed spawners. These are fish that return in year t but delay spawning to the year after (t+1). They are specific to each stock-unit and may vary among years (so far, 0 for all stock-units except Russia);
- The biological characteristics of fish at the spawner stage. These include the proportion of females and the average egg deposition per female. These are defined for 1SW and 2SW fish separately, specific for each stock-unit and may vary among years.

*Observation equations (likelihood):*

The model is fitted to time series of data with observation errors. These include:

- Abundance at the return stage (1SW and MSW)
- Homewater catches (1SW and MSW)
- Catches of all marine fisheries (1SW mature, 1SW non-mature, MSW)
- Proportion of the different origins in the catches at sea

The full likelihood function for the general state-space model is built from the combination of all observation equations for the returns, homewater catches and catches at sea, for 1SW and MSW separately.

A sequential approach is used that consists of (i) processing observation models separately to reconstruct probability distributions that synthesize observation uncertainty around the time series of catches and returns for the 25 stock-units; and (ii) using those distributions as pseudo-likelihood approximations in the population dynamics state-space model.

Using such a sequential approach represents a trade-off between model realism and computational efficiency but has two main advantages. First, it enhances computational efficiency because building an integrated model that explicitly integrates specific observation models for each stock-unit would dramatically increase the complexity of the full model. Secondly, the sequential approach considerably enhances modelling flexibility. Indeed, separating out the population dynamics from the models that integrate the raw data to provide estimates of returns or catches at the scale of each stock-unit provides a flexible framework where any improvements of the observation models can be made without impacting the structure of the population dynamics model. Hence, continuous improvement of the models developed locally to maximize the use of available data and knowledge can be envisaged with minimum impacts on the population dynamics model and on the entire workflow.

Probability distributions for returns and catches are derived from a variety of raw data and observation models, specific to each stock-unit (except for the mixed stock fisheries at sea) as originally developed by ICES to provide input for PFA models. These are directly derived from the Run Reconstruction (RR) models run by ICES WGNAS, separately for the three continental stock groupings.

*Catch allocations for the marine distant fisheries:*

As an important evolution from the PFA modelling framework, the catches in the marine distant fisheries at Faroes and West Greenland are now allocated using updated genetic data.

*Faroes fishery*

For each of the three age-classes separately (maturing 1SW(m), non-maturing 1SW(nm) and MSW) and for each year, total catches of fish caught at Faroes are assumed to be observed with lognormal errors, with relative error (CV) derived from specific models that integrate the uncertainty essentially due to the proportion of unreported catches and of wild fish in the catches (historically, catches included a component of escapees from salmon farms).

Total catches of 1SWm and 1SWnm and 2SW at Faroes (assumed in the model to comprise European fish only – while NAC salmon have been observed, their abundance is negligible) are allocated to the different stock-units following a two levels allocation rule:

- **Level 1**. First, the total catches are allocated to three large groups of stock-units using proportions based on the relative harvest rate estimated from genetic assignment data (pers. com, 2023; see Section 4.3):
  - The Southern European CSG (France, UK – England and Wales, Ireland, UK – Northern Ireland – FO, UK – Northern Ireland – FB, UK – Scotland East, UK – Scotland West and Iceland South-West).
  - The southern part of the Northern European CSG, that comprises Iceland North-East, Sweden, Norway South-East, Norway South-West and Norway Middle.
  - The northern part of the Northern European CSG, that comprises Norway North, Finland, Russia Kola Barents, Russia Kola White Sea, Russia Arkhangelsk Karelia and Russia River Pechora.
  - Genetic data indicate that proportion of those fish in the Faroes catches is much less than their proportion in the abundance, which indicates different (further east and north) migration routes.
- **Level 2**. Second, within each of the three groups, catches are assigned to the different stock-units within those groups assuming that exploitation rates are homogeneous among stock-units.

*West Greenland fishery.*

This fishery is assumed to operate on the 1SW component of the populations. Catches of 1SW at West Greenland may originate from any of the 25 stock-units from all CSG. The total number of 1SW fish caught at West Greenland is assumed to be observed with lognormal errors, with relative error (CV) arbitrarily fixed to 5%. A CV of 5% is a conservative measure of uncertainty relative to the one that would result from the conversion from catch in weight to number of fish (low uncertainty due to the very high sample size available to calculate the mean weight of fish (WKBSalmon 2023, pers. com.).

Total catches are then allocated to the different stock-units following a three levels allocation rule (see Section 4.3):

**Level 1**. First, total catches are allocated to the North American or European complexes using proportions calculated from a compilation of individual assignment data based on discriminant analyses of scale characteristics and genetic analyses.
**Level 2**. Second, within the European stock complex, catches are allocated to the Southern or Northern European CSG using proportions calculated from a compilation of individual assignments (WKBSalmon 2023, pers. com.; see Section 4.3).
**Level 3**. Third, within each of the three groups, catches are assigned to the different stock-units that compose the group assuming that exploitation rates are homogeneous among stock-units.

## 5.4 MCMC simulation using Nimble

Bayesian posterior distributions were approximated using Monte Carlo Markov Chain (MCMC) algorithms in *Nimble* (https://r-nimble.org/) through the *rnimble* (www.Rproject.org) package.

- A suite of programs in R have been developed that provide a consolidated streamline from hindcasting to forecasting (see Lemaire-Patin *et al.*, 2023 for guidelines to use the suite of R programs) (Figure 5.2).

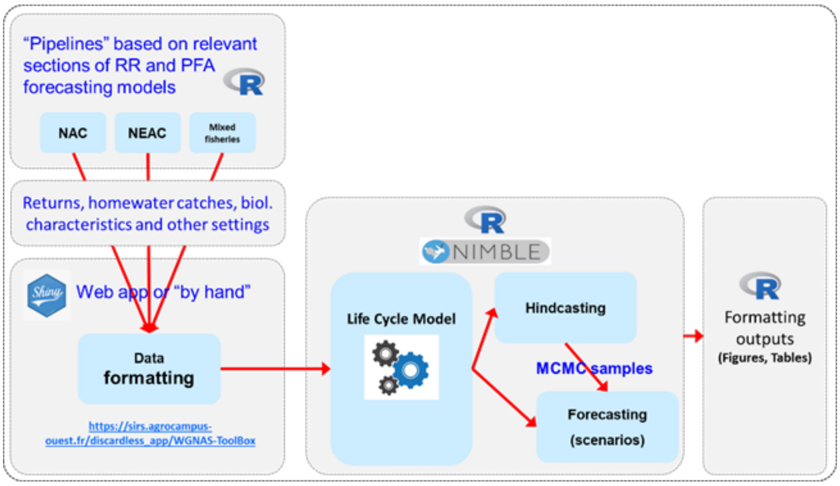


**Figure 5.2 Streamline for stock assessment and catch advice using the life cycle model.**

# 5.5 Model diagnosis and sensitivity analysis

## 5.5.1 Convergence of MCMC simulations

Sampling efficiency for this model is relatively low, meaning that a long MCMC simulation is needed to obtain reasonable convergence to the posterior distribution and reliable results. A MCMC setting with 10 chains run in parallel, each one with 250 000 iterations is recommended.

- Convergence of MCMC chains is assessed using the *Rhat* Gelman-Rubin statistic as implemented in the R Coda package (*gelman.diag*), complemented by an evaluation of the effective sample size as implemented using R Coda package (*effectiveSize*).

Results of convergence diagnostics indicate that with the MCMC settings mentioned above, MCMC chains of all variables in the model have converged (the Gelman-Rubin *Rhat* statistics stands well below the 1.05 rule of thumb for almost all variables). The effective sample size is also higher than 1000 for almost all variables, which is usually large enough to make good Monte Carlo approximations for any key management quantities, including probabilities in the tails of the posterior.

## 5.5.2 Model diagnosis

The quality of fit of the model to the different data sources is assessed through the qualitative comparison between the posterior distribution of state variables in the model and the associated data (Rivot *et al.*, 2023). When observation errors are associated to one data source, the posterior distribution of the state variable is compared to the probability distribution that corresponds to observation errors (e.g., lognormal distribution of returns with known expected men and standard deviation).

Results show that the model fits well to all data sources. The fit to the homewater catches is very tight, which is directly explained by the very low variance imposed on observation errors around the point estimates of homewater catches (lognormal with CV arbitrarily fixed to 0.05%).

In a previous version of the model, Olmos *et al.* (2019) had implemented the calculation of Bayesian *p*-values for posterior checking. Those are useful synthetic indicators of the capacity of the model (once fitted *a posteriori*) to replicate data similar to those used to fit the model. Similar diagnostics of quality of fit will be developed in the future.

Other model diagnosis should be implemented in the future to assess the stability of the model. A recommendation of the Benchmark is to develop retrospective patterns diagnostics such as the Mohn's diagnostics (Mohn, 1999) that are commonly investigated to validate fish stock assessment models.

### 5.5.3 Sensitivity analysis

*Egg-to-smolt survival*

The smolt-to-PFA survival is partly confounded with the egg-to-smolt survival in the model. In the absence of smolt production data at the scale of stock-units, the parameters of the freshwater-phase dynamic were assumed to vary randomly (lognormal with CV=0.4) around a fixed average value (0.7%).

Olmos *et al.* (2019) explored the sensitivity of the results to between-years stochastic variation in the egg-to-smolt survival. Because part of the overall inter-annual variability in the survival is captured by the egg-to-smolt survival, increasing (decreasing) the coefficient of variation of the inter-annual variability in the egg-to-smolt survival results in greater (lower) temporal variation in egg-to-smolt survival estimates. However, the eggs-to-smolt transition does not capture any particular temporal trend and overall time trends in post-smolt survival time series were robust to an increase in the egg-to-smolt inter-annual variance.

Massiot-Granier (2014) and then Olmos *et al.* (2019) explored the sensitivity of the results to the introduction of density-dependence in the egg-to-smolt survival. The effect of introducing density dependence was relatively marginal change in the inter-annual stochasticity of egg-to-smolt survival.

*Natural mortality rate after the PFA stage*

Because of the absence of an abundance audit point between the smolt and the return stage, the smolt-to-PFA survival is partly confounded with the natural mortality after the PFA stage. Also, the proportion maturing as 1SW is partly confounded with the difference in natural mortality between 1SW and MSW fish (Chaput, 2012). Hence, the natural mortality rate after the PFA stage was fixed, assumed identical for maturing and non-maturing fish and constant in time, as per the choice made by ICES for the PFA forecast models (ICES 2004).

Massiot-Granier *et al.* (2014) explored the sensitivity of the results to the average value of *M*. As expected, *M* is a scaling factor in the model that balances the smolt-to-PFA survival rate. The lower the expected mean of the prior on *M*, the lower the posterior estimates of the smolt-to-PFA survival. Changing the expected value of *M* also affects the probability of maturing as 1SW. A higher *M* slightly decreases the differential of cumulated natural mortality between 1SW and MSW fish, which leads to higher estimates of the proportion maturing as 1SW.

Massiot-Granier *et al.* (2014) explored an alternative model setting where temporal changes in the ratio of return rates of MSW relative to 1SW fish result from variations in the natural mortality rate of MSW fish after the PFA stage, rather than from changes in the proportion maturing. The proportion maturing is assumed constant, as is the natural mortality rate of 1SW fish, but between-year variability of the natural mortality rates of MSW relative to 1SW fish is accounted for. Results revealed that estimates of abundance and transition rates from eggs to PFA were not sensitive to changes from the baseline to this alternative hypothesis. But the mortality rates of non-maturing fish after the PFA stage varies notably, with a pattern of variation very similar to that of the proportion maturing.

This is a critical issue that future research should address. Indeed, the alternative hypotheses may have important implications for the management of high seas fisheries. Considering a higher mortality rate for MSW fish after the PFA stage would reduce the expected impact of catch regulations for the distant water fisheries aimed at preserving future MSW fish. A response to environmental changes that would affect differently 1SW and MSW fish during their migration routes could also justify introducing different temporal variation in natural mortality between 1SW and 2SW fish.

## 5.6 Multiple years forecast and provision of catch advice

### 5.6.1 The LCM is a natural tool to forecast

Once fitted to the data, the life cycle model is used to forecast the population dynamics during $n_f$ years starting after the last year of the assessment, under any specific scenario. Forecasts are probabilistic and allow to compute, for any scenario, the probability distribution of any quantity in the model while integrating both process and parameter uncertainties.

Following ICES WGNAS practices, this forecast was made under different catch scenarios in the Faroes and West Greenland mixed stock fisheries. We used probabilistic forecasts from the model to evaluate the probability that future returns of adult fish (after the last years of the hindcasting phase) exceed management objectives for different catch options in the West Greenland and the Faroes fisheries.

The forecast horizon is typically 3 years ahead as required by NASCO (but note that this can be changed easily if a longer or shorter forecast horizon is required).

A critical advantage of the LCM framework is that the same life cycle model is used for fitting the historical time series and forecasting. In practice, one unique life cycle model code written in Nimble is used for both the hindcasting and the forecasting phases. This ensures model consistency between the two phases and limits errors as no re-coding is required between the two phases. In addition, the posterior MCMC samples from the hindcasting phase can be easily re-used to propagate parameters uncertainty in the forecasts.

### 5.6.2 Propagation of uncertainty in the forecasts

Forecasts integrate and propagate all sources of uncertainty from the hindcasting phase. They integrate both process errors, e.g., environmental stochasticity due to the stochastic temporal variations of key transitions rates and parameters' uncertainty quantified by the joint Bayesian posterior distribution of all estimated parameters.

For any given scenario, uncertainty is integrated through Monte Carlo simulations, by simulating a large number of population trajectories with parameters and the abundance in different life stages randomly drawn in the joint posterior distribution. This captures the covariance structure among all unknowns in the model.

When forecasting during a short three-year time horizon, most of the uncertainty in the forecasts comes from the uncertainty in the key transition rates that control the smolt-to-PFA survival (the marine productivity) and the proportion of fish at the PFA stage that mature in their first year at sea. Forecasts are mostly conditioned by the hypotheses made to model the temporal variation of key demographic parameters. In particular, for each simulated trajectory, stochastic variations of the smolt-to-PFA survival and the proportion of maturing PFA are forecasted following the multivariate random walks for those parameters. Because of the random walk hypothesis, the forecasted smolt-to-PFA survival and proportion maturing PFA during the forecasting period will remain at the same average level as the last year of the fitted time series, but with an uncertainty that increases quickly with time due to error propagation through the random walk.

### 5.6.3 Risk analysis framework for the West Greenland and the Faroes fishery

Probabilistic forecasts from the model are used to evaluate the probability that future returns of adult fish reach management objectives for different catch options in the West Greenland and the Faroes fisheries. As an important contribution, the life cycle model provides a unified framework for evaluating catch options for the Faroes and West Greenland for all stock-units separately or simultaneously.

*Parameterizing scenarios*

For the Benchmark, we parameterized catches scenarios ranging from 0 to 500 tons (11 scenarios with values every 50 tons) for both the Faroes and the West Greenland catches.

Catch options

For each scenario, catch weight options are converted to total number of fish caught after consideration of unreported catches rates, the conversion from weight to number of fish (using mean weight of fish) and sharing agreement rule. There is no uncertainty in this conversion so far.

*Sharing agreement*

The current version of the model uses sharing agreement options that were defined historically as management options founded on a social agreement on what might be an equitable use of resources. Implementation in the LCM consists in setting homewater catches and all other marine fisheries at zero and scaling the total catches at Faroes or West Greenland following the sharing agreement rule. For the West Greenland fishery, the sharing agreement rule was defined historically as 40% to West Greenland fisheries: 60% to homewater fisheries. This means that a scenario of say, 100 tons actually corresponds to 100/0.4 = 250 tons of fish caught. For the Faroes fishery, the sharing agreement rule was defined as 8.4%: 91.6%. This means that a scenario of say, 100 tons, actually corresponds to 100/0.084 = 1190 tons of fish caught.

*Catches allocation*

In forecasting, catches at Faroes and West Greenland from the scenarios are allocated to the different continental stock groups and stock-units the same way Faroes and West Greenland catches are partitioned in the model during the hindcasting phase. The proportions used to allocate the catches among stock complexes (proportions at Level 1 for the Faroes fisheries and at Levels 1 and 2 for the West Greenland fishery) are considered constant during the forecasting phase (no time variations). They are set to the average realized proportions calculated in the model over the last five years of the hindcasting phase. The posterior uncertainty (from MCMC draws) around those proportions is therefore considered in the simulations. Within each stock complex, proportions used to allocate the catches among stock-units (proportions at Level 2 for the Faroes fishery and at Level 3 for the West Greenland fishery) are calculated in the model as the relative proportions of abundance before the fishery. This is therefore equivalent to the homogeneous harvest rate hypotheses used in the forecasting phase. The posterior uncertainty (from MCMC draws) around those proportions is also considered in the simulations.

*All other fisheries*

In all scenarios, all other fisheries except the Faroes and West Greenland are set to 0 catches. This means that the framework is not expected to provide any advice on the way the total catches should be managed by the different countries.

*Other settings*

All other parameters needed to define the population dynamics during the forecasting phase (e.g., smolt-age proportions, proportion of females in returns, fecundity, etc) are set to their averages calculated over the last five years of the hindcasting phase and considered constant (no time variation) during all forecasted years.

*Probability to reach Conservation Limits or management objectives*

Management objectives (MO) are defined in the number of eggs and are directly deduced from the values provided to ICES by the different stock-units/countries/jurisdictions. Management objectives are based on Conservation Limits (CLs) as defined by ICES and NASCO or using other rules agreed by ICES.

For any scenario, the forecasted egg deposition by spawners (e.g. after all potential fisheries) is then compared to the MOs, as defined above. Forecasts are probabilistic and allow to compute, for any scenario, the probability that the egg deposition meets or exceeds the MOs. All probabilities are directly calculated from Monte Carlo trials.

*Sea-age class*

It is straightforward to calculate the egg deposition realized by 1SW and MSW fish combined, or for the two sea-age classes separately. The compliance to the MOs can be provided for all sea-age classes combined or for the two sea-age classes separately. The model can also assess the proportion of eggs spawned by MSW fish. Assessing the compliance to MO for MSW fish specifically or the proportion of eggs spawned by MSW fish allows an investigation of the sensitivity of this component of populations to the catch scenarios. This is especially the case of the West Greenland fishery that primarily harvests the 1SW non-mature component of the salmon abundance at sea and the Faroes fishery that preferentially targets the MSW fish on their returning migration to homewaters. The sensitivity of the proportion of eggs spawned by MSW fish to these fisheries is an indicator of the selectivity of the fishery relative to the sea-age class and of its potential evolutionary impact.

**Note**. For NAC stock-units, the probability to achieve the MSW CL or MO is calculated by controlling for the proportion of fish that are truly MSW among the large salmon component. These proportions are provided for each stock unit as fixed or annually varying values from the run reconstruction inputs (See Sections 4.1 and 4.2).

*Spatial aggregation and probability that several stock-units reach MO simultaneously.*

The model works at the scale of the 25 stock-units, but results can be aggregated at any scale. This allows managers to evaluate both individual (country/jurisdiction level), aggregated and simultaneous achievement of MO at the scale of continental stock groupings.

- **Country scale.** Management objectives used by ICES are only available at a more aggregated spatial scale than stock-units defined in the life cycle model. Specifically, one MO is available for Scotland (sum of Eastern Scotland and Western Scotland in our model), one MO for Northern Ireland (sum of Northern Ireland FO and Northern Ireland FB), one MO for Norway (sum of 4 stock-units in our model, South-East Norway, South-West Norway, Middle Norway and North Norway) and one MO for Russia (sum of 4 stock-units in our model, Russia Kola Barents Russia Kola White Sea, Russia

Arkhangelsk Karelia and Russia River Pechora). To be compared to the MO defined by ICES, egg depositions are summed to match the spatial scale considered for that MO.

- **Stock grouping.** One can also calculate the probability of achieving MO at the scale of any stock grouping (e.g., sum of all stock-units in North America, Southern Europe, Northern Europe)
- **Simultaneously.** One can also calculate the probability of MO being achieved by all management units simultaneously within a same stock grouping (i.e. in the same given year), as is currently provided for catch advice at West Greenland (ICES 2021). This probability integrates the spatial covariation in the return among stock-units.

## 5.7 Outputs of the LCM

The results presented during the Benchmark were obtained using the data supplied to the ICES WGNAS in 2023 (ICES, 2023). The time series of data is therefore 52 years from 1971 to 2022 (for the hindcasting phase). Following discussions during the benchmark process, these data are supplemented by new data on the origin of fish caught at Faroes (proportions to allocate Faroes catches among three sub-complexes: Southern European complex (southern and northern) and part of the Northern European complex; WKBSalmon 2023, pers. com.; see Section 4.4) and on the origin of fish caught at West Greenland (proportions to allocate European fish to the N- and the N-NEAC complexes; WKBSalmon 2023, pers. com.; See Section 4.4). Forecasting to assess catch options at West Greenland and Faroes was performed for 3 additional years (2023 to 2025).

### 5.7.1 Hindcasting – Fitting the LCM to the time series of data

*Convergence of MCMC chains*

Results of convergence diagnostics indicate that with the MCMC settings mentioned above, MCMC chains of all variables in the model have converged. The Gelman-Rubin Rhat statistics stand well below the 1.05 rule of thumb for almost all variables. The effective sample size is also higher than 1000 for almost all variables.

*Model fit to the different data sources*

The fit to the different data sources is assessed through comparison between the posterior distribution of state variables in the model and the associated observations for the four main sources of data. Results show that the model fits well to all data sources. The fit to the homewater catches is very tight, which is directly explained by the very low variance imposed on observation errors around the point estimates of homewater catches (lognormal with CV arbitrarily fixed to 0.05%).

*A widespread decline of abundances in all CSG*

The model estimates time series of all key life stages for all stock-units or for any aggregation of stock-units at the scale of stock-units or countries/jurisdictions (see Figure 5.3 for the example of Quebec) or aggregated at the scale of stock complexes (see Figure 5.4 for the aggregation at the scale of the Southern NEAC).

Time series of total PFA (total, mature and non-mature) aggregated at the scale of CSG show very similar continuous declines by a factor 3, between the 1970s and the 2010s (Figure 5.5) with a stronger decline for the NAC CSG. The decline in PFA is marked by a strong decrease in abundances in the 1990s.

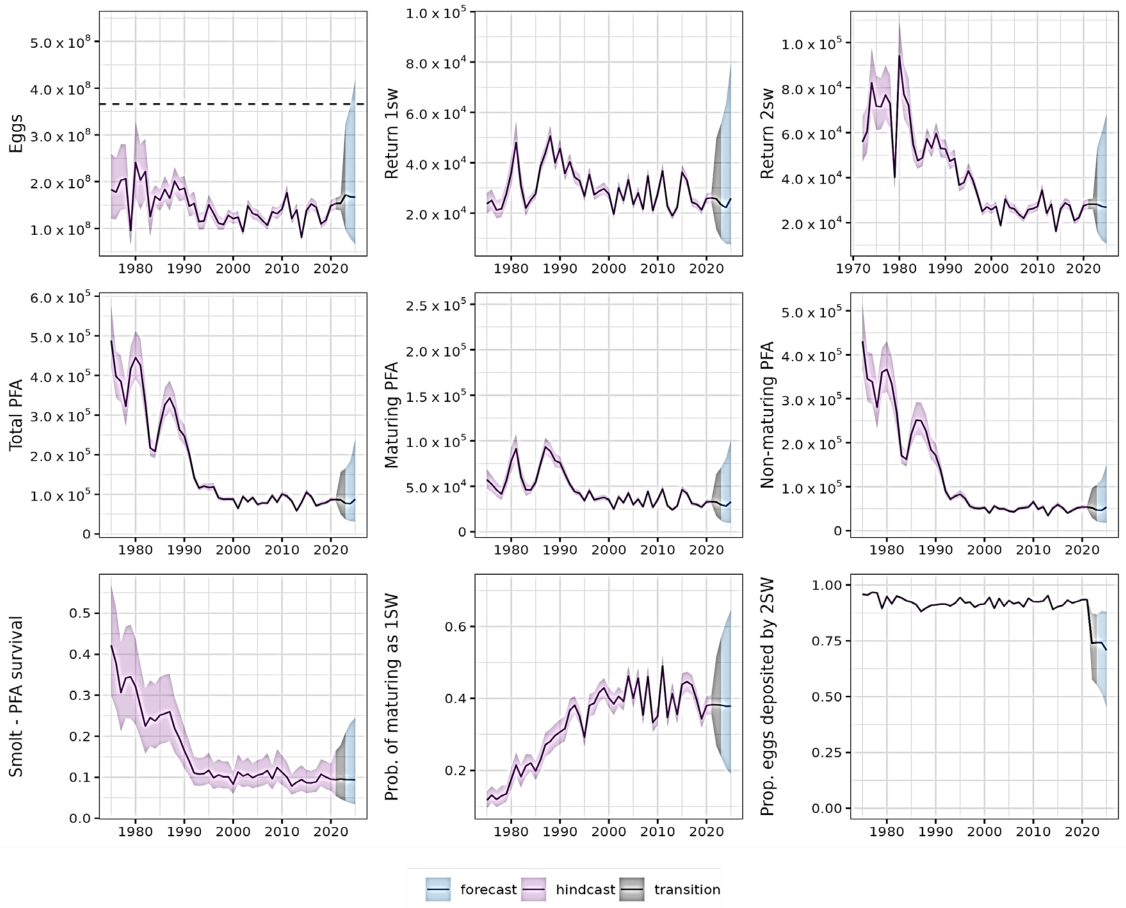


**Figure 5.3. Quebec. Posterior probability distributions for the key life stages for all stock-units (or aggregate of stock-units at the scale of countries). Pink shaded: hindcasting on the historical time series 1971-2022. Blue and grey shaded: forecasting obtained under a scenario with 0 catches in all fisheries. Horizontal dotted lines in the top left panel is the management objectives (in total eggs 1SW + MSW).**

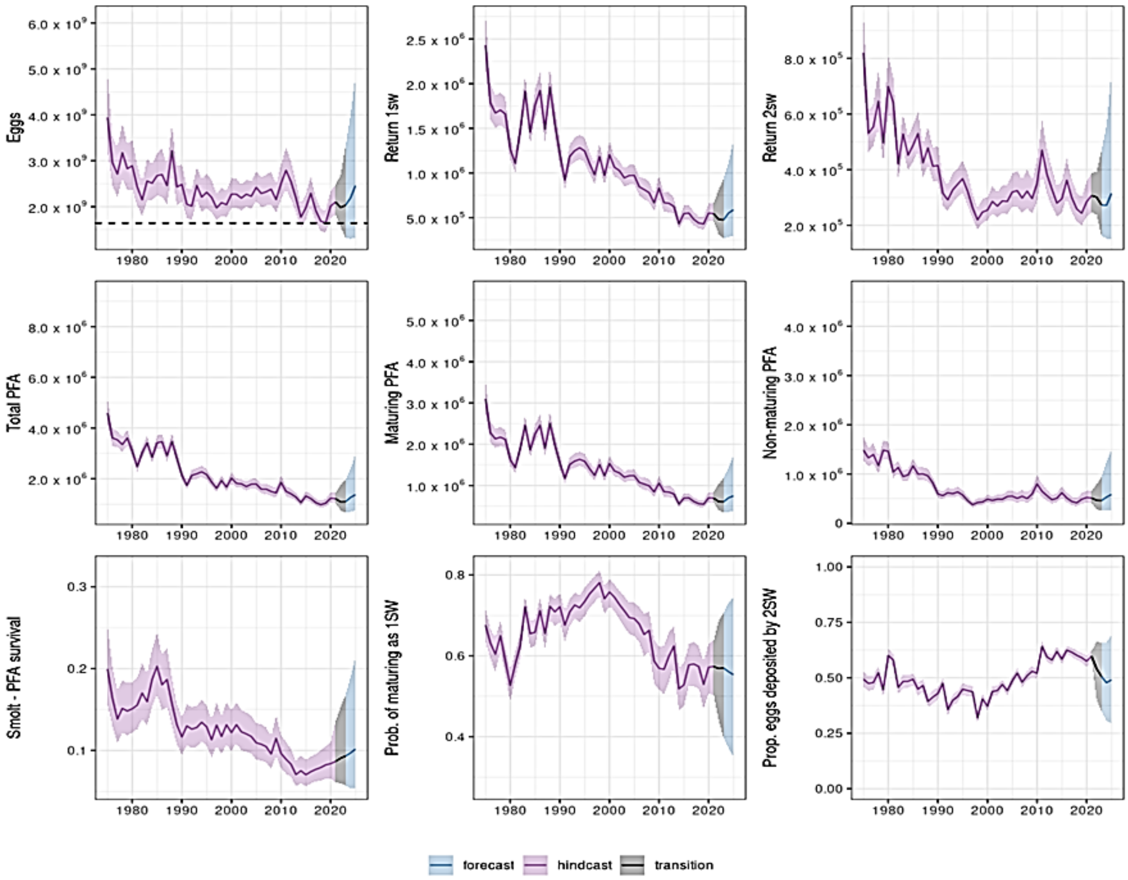


**Figure 5.4. Southern Europe. Posterior probability distributions for the key life stages aggregated for all stock-units of Southern Europe. Pink shaded are: hindcasting on the historical time series 1971-2022. Blue and grey shaded area = forecasting obtained under a scenario with 0 catches in all fisheries. Horizontal dotted lines in the top left panel is the management objective in eggs (total 1SW + MSW).**

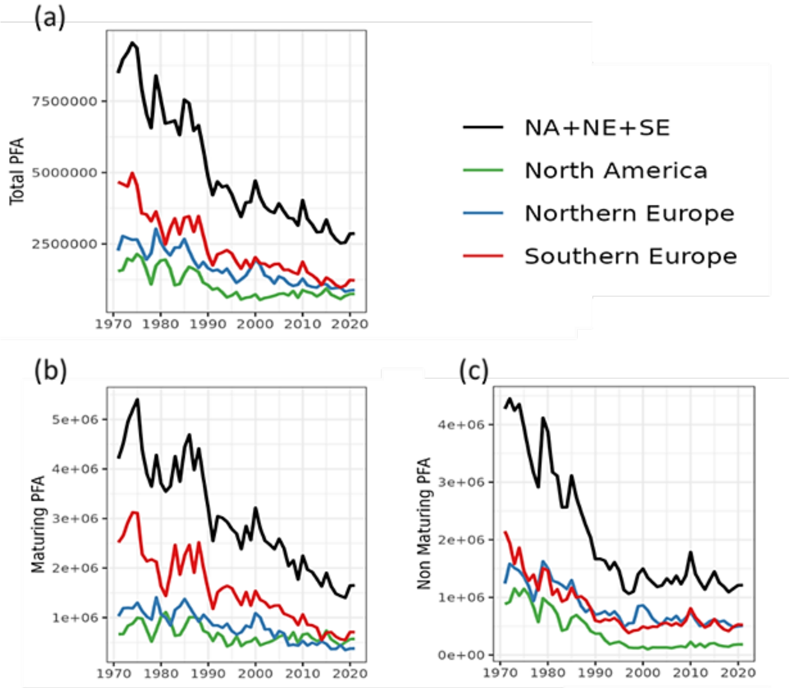


**Figure 5.5. Abundances estimated at the PFA stage for the North Atlantic and for all stock-units for the three continental stock groups (median of the marginal posterior distributions: (a) Total PFA (maturing + non-maturing); (b) PFA maturing; (c) PFA non-maturing.**

*Coherence in temporal variations of post-smolt survival and proportion of fish maturing as 1SW*

The time-series of post-smolt survival for the 25 stock-units show a common decreasing trend over years (Figure 5.6 a). The trends averaged over all stock-units of the same CSG exhibit slightly different tendencies over the years. Those patterns are consistent with the decline observed in the abundance at the PFA stage. The post-smolt survival in NAC exhibited a strong decline by a factor of 3 in the period 1985-1995. This decline is also observable in S-NEAC with a sharp decline by a factor of ~1.8 in 1987. The trend in N-NEAC shows a continuous and smooth decline over the period. The majority of pairwise correlations are positive (see Rivot *et al.*, 2023 for more details). In general, correlations are stronger between geographically close stock-units. The results show strong correlations for stock-units within NAC, followed by NEAC-S and NEAC-N.

Time trends in the proportion of the PFA maturing (from 1SW to MSW) also show a strong coherence among stock-units (Figure 5.6 b). Overall, there is an increasing trend from the 1970s to the 1990s that corresponds to declines in the proportions of MSW fish in the returns followed by a levelling off or even a decline from the 2000s. As observed for the post-smolt survival, most of the pairwise correlations are positive across the 25 stock-units (see Rivot *et al.*, 2023 for more details). In general, the correlations are stronger for geographically close stock-units. The results show strong correlations for stock-units within NA, followed by S-NEAC and NE.

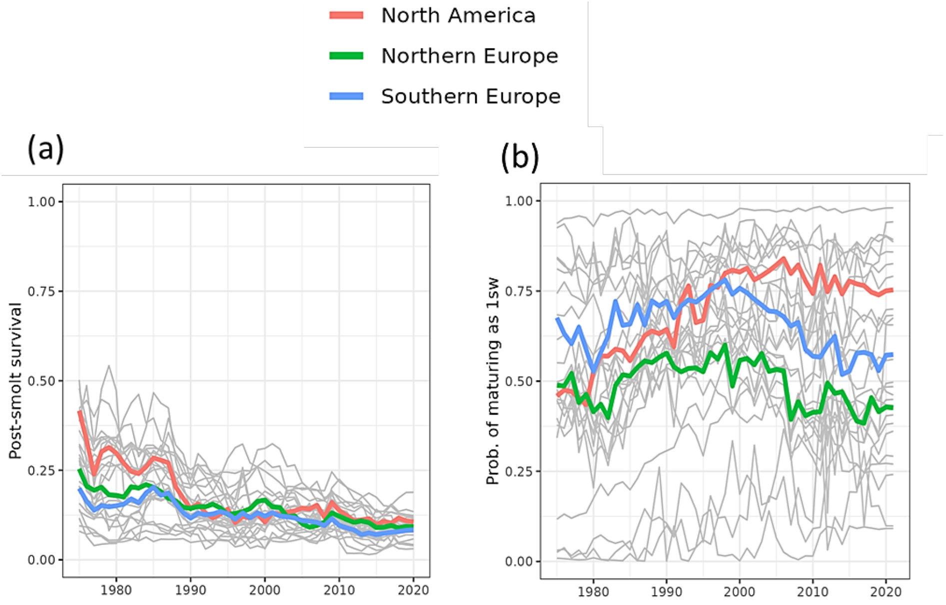


**Figure 5.5. Smolt-PFA survival (in the natural scale; a) and proportion PFA maturing as 1SW (in the natural scale; b) for the 25 stock-units (thin grey lines) and averaged over the three continental stock groups (thick colour lines) (median of the marginal posterior distributions). The first 5 years are not represented as the inferences are too sensitive to initialization of the first cohorts.**

### 5.7.2 Forecasting and risk analysis

*An example of forecast for Quebec*

The model allows for forecasting abundances for all life stages in the model under the different catch options at Faroes or West Greenland.

As an example of forecast results obtained for Quebec under the scenarios of 0 catches in both Faroes and West Greenland (Figure 5.3, example of Quebec), results show how uncertainty in the forecasts increases with forecasting horizon (i.e. number of years of forecast). The propagation of uncertainty is mostly the consequence of uncertainty propagation through time in forecasts of the post-smolts survival and proportion maturing PFA modelled as multivariate random walks.

From those forecasts it is straightforward to compute the probability that the egg deposition (total, 1SW + MSW component of the returns or separately for the two sea-age classes 1SW and MSW) is greater than the MOs defined for any country/regions in the model or at any higher aggregation level (country/regions, aggregated at the scale of stock complex, or simultaneously for all stock-units in the same stock complex).

*Catch options for the West Greenland mixed stock fishery*

For West Greenland catch options, the probability to achieve MO is illustrated by comparing the egg deposition by MSW fish only with the MSW MOs.

As expected, stocks from North America such as Labrador, Quebec and Gulf are highly sensitive to catch options at West Greenland (Figure 5.7a-b-c). The probabilities of achieving MSW MOs for those stock-units dramatically decreases when catches increase. This is expected as the relative harvest rate of North American fish in the catches at West Greenland is much higher than for European fish in recent years. The sensitivity to catch options is further increased for stock-units where returns are dominated by MSW salmon as only this component of the population is impacted by the West Greenland fishery. Stock-units from southern Europe are less sensitive to catch options at West Greenland. This mostly results from a relative harvest rate at West Greenland that is much lower than for North American stock-units in recent years. Catch options at West Greenland have only minimal influence on the probability of achieving MOs for northern European stocks. This is expected as these stocks represent only a very low proportion of the catches at West Greenland (less than 5% of the total fish harvested in West Greenland).

When assessed at the scale of stock complexes (i.e. by comparing the total egg deposition with the MOs aggregated at the scale of stock complex), the North American stock complex logically reveals the most sensitivity to catch scenarios at West Greenland (Figure 5.7d). Sensitivity of the southern European stock complex is limited and the north European stock complex is insensitive. As expected, the probability that all stock-units in the same continental stock grouping achieve their MOs simultaneously is even lower (Figure 5.7e). This probability is near zero for North America and Southern Europe stock complexes, regardless of the catch options.

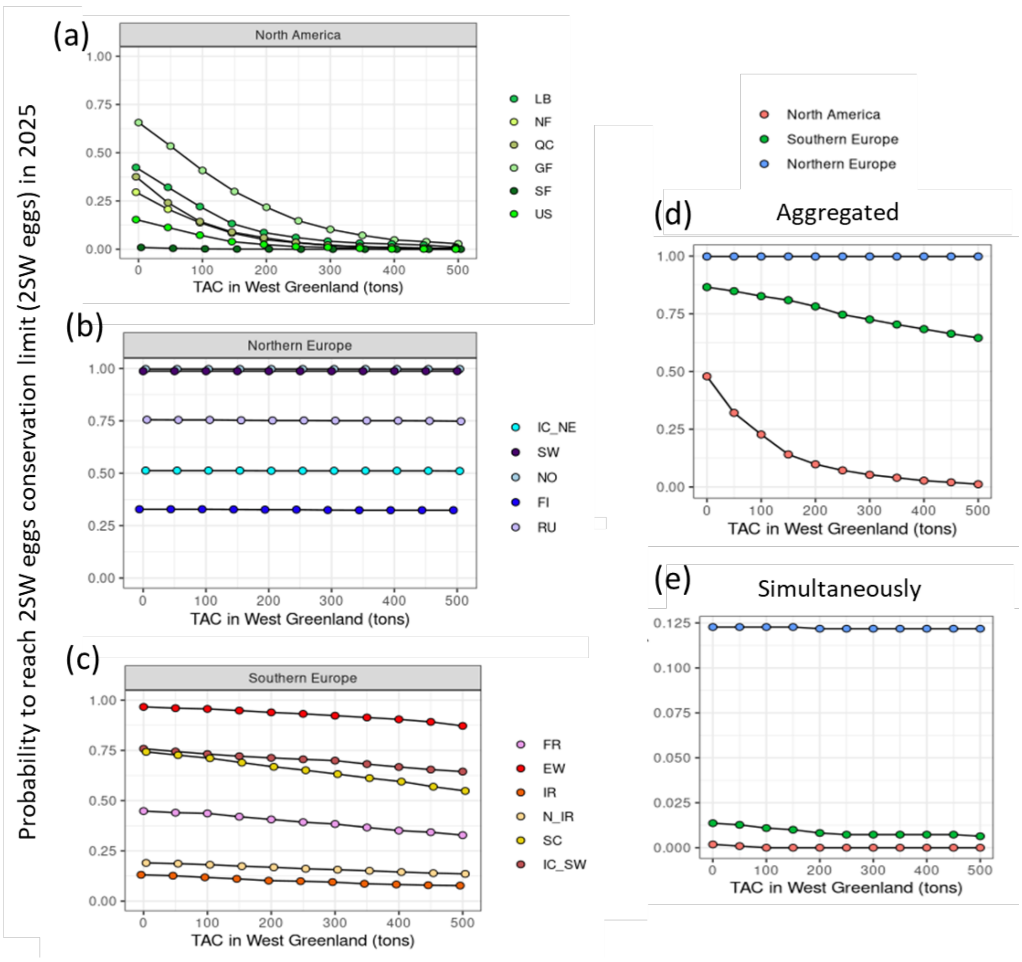


**Figure 5.6. Catch options at West Greenland (catch options 0-500 tons; 0 catches for all other fisheries). (a-b-c) Probability to achieve MSW Conservation Limits obtained under different catch options after 3 years of forecasting (year 2025; last assessment year = 2022) (a-b-c) for all countries/regions individually; (d) aggregated by stock complex; (e) simultaneously for all stock-units of the same complex. Only very few fish originated from Northern Europe are caught at West Greenland. This explains why the probability to achieve CL for northern European stock-units is fairly insensitive to West Greenland catch scenarios.**

*Catch options for the Faroes mixed stock fisheries*

For Faroes catch options, the probability to achieve MOs is illustrated by comparing the total egg deposition (by 1SW + MSW fish) with the MOs expressed in total number of eggs.

Catch options at Faroes influence the probability of achieving MOs for European stock-units only (Figure 5.8a-c). Although North American salmon were caught in the Faroes fishery (see section 4), the numbers were so small that it is assumed they are absent in the model parameterisation. Therefore, stock-units from North America are in-sensitive to catch options at Faroes as fish from North America. The sensitivity is slightly higher for country/regions with relatively high proportions of MSW in their returns (e.g. UK – England and Wales, and UK – Scotland).

When assessed at the scale of stock complexes (i.e. by comparing the total egg deposition with the MOs aggregated at the scale of stock complex), the southern and northern European stock complexes reveal similar sensitivity to Faroes catch options (Figure 5.8d). As expected, the probability that all stock-units in the same continental stock grouping achieve their MOs simultaneously is even lower (Figure 5.8e). This probability is notably lower for Southern Europe than for Northern Europe.

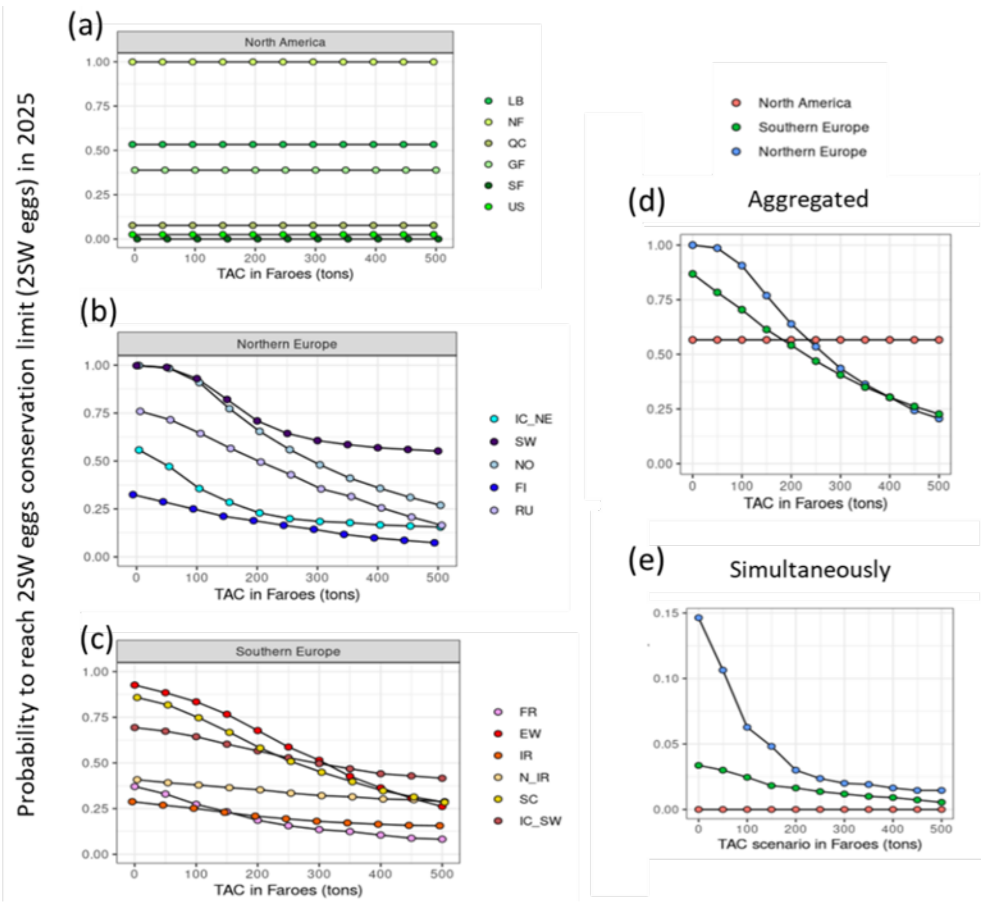


**Figure 5.7. Catch options at Faroes (catch options 0-500 tons; 0 catches for all other fisheries). (a-b-c) Probability to achieve the Conservation Limits (1SW+MSW) obtained under different catch options after 3 years of forecasting (year 2025; last assessment year = 2022) (a-b-c) for all countries/regions individually; (d) aggregated by stock complex; (e) simultaneously for all stock-units of the same complex. The model assumes no fish from North America are caught at Faroes. The probability to achieve CL for North American fish therefore is un-sensitive to Faroes catch scenarios (not shown).**

# 5.8 Comparison with the PFA modelling framework and benefits of the LCM

## 5.8.1 Expected differences in forecast and risk analysis between life cycle and PFA models

Given the structural differences between the PFA and LCM, important differences are to be expected in the assessment (hindcast and forecast) and these result from two main sources:

- The demographic structures of the PFA and LCM are fundamentally different for the NAC stock-units. Indeed, PFA models rely on different life history hypotheses depending on CSG: N-NEAC and S-NEAC PFA models consider both 1SW and MSW life histories while the NAC PFA model considers MSW life history only. This may create strong differences especially in the estimation of egg deposition, of the marine productivity and on the abundance at the PFA stage, that may propagate to the forecast.
- The LCM and the PFA models consider uncertainty differently, which can induce major differences in hindcast, forecast and risk analysis.
    - In the LCM all latent variables are correlated through the life cycle structure whereas in the PFA model no demographic link exists between the cohort (between returns and spawners, similar to a stock recruitment dynamic). This changes how the uncertainty is propagated through the latent variables and parameters.
    - In the PFA models, the stock abundances (lagged eggs for NEAC and lagged spawners for NAC) are defined in the models through a prior distribution which is not updated within the models and so the uncertainty is not propagated through the other latent variables and parameters. Here again, this might result in important difference in terms of how the uncertainty is quantified and propagated between the life cycle and PFA models.
    - Finally, in PFA models, only the returns are associated with a likelihood function, whereas in the LCM the likelihood function includes the distribution of returns, the distributions of both freshwater and fisheries catches and the proportion to allocate the catches to each stock-units.

## 5.8.2 Comparison of outputs of the new LCM and PFA models

The comparison described below is based on the version of the Life Cycle Model developed in 2021 that is an extension of the model proposed by Olmos *et al.* (2019) and that differs from the updated version presented. The catch allocation rule used in the LCM for the mixed stock fisheries in Faroes and West Greenland is different to the one used in the PFA models. In particular, in the PFA models, the catch allocation rule at West Greenland allocates catches among stock-units within the same complex in proportion to the pre-fishery abundance. In the LCM, catches at West Greenland are allocated using proportions based on genetic data. The comparison is based on data of WGNAS 2018 (so data 1971–2017) (ICES, 2018).

*Hindcast*

*Trends in key demographic parameters and PFA*

As expected, for European stock-units, because there is no difference in the demographic structure between the LCM and the PFA models, posterior estimates of abundances (egg deposition, PFA, returns) and demographic parameters (productivity and proportion of fish maturing as 1SW) revealed highly consistent results between the PFA models and the LCM (see example of UK – Scotland at Figure 5.9; other details in Olmos *et al*., 2023).

Results are less consistent for North American stock-units. Figure 5.10 and Figure 5.11 present the results for two stock-units, Quebec and Newfoundland, which illustrate two contrasting situations (but see Olmos *et al.*, 2023 for detailed results on all North American stock-units). The contrast is mainly attributed to the fundamental difference in the demographic structure between LCM and PFA models for North America, with PFA models for NAC that consider the dynamics of 2SW only. As a direct consequence, for stock-units with returns largely dominated by 2SW (US, Scotia-Fundy, Quebec, Gulf), 1SW fish contribute marginally to the abundance of returns (and then of PFA) and to the egg deposition and the posterior estimates of abundances and marine productivity show similar trends and values for both LCM and the PFA models. However, for stock-units having returns largely dominated by 1SW (Labrador and Newfoundland), strong differences in the dynamics are revealed. As expected, variables and parameters directly related to non-maturing fish (e.g., 2SW returns and non-maturing PFA) show consistent temporal patterns and values between PFA and LCM (Figure 5.11). But posterior estimates of egg deposition from the LCM are estimated to be 5 times larger than estimates from PFA models, which directly results from the contribution of 1SW fish (in addition to 2SW) to the egg deposition and abundance which is not considered in the PFA models that consider 2SW fish only.

*The LCM produces more precise (lower uncertainty) estimates and forecasts*

A second difference between the PFA models and the LCM is that the LCM produces more precise (lower uncertainty) estimates of abundance and key demographic parameters (Figure 5.9, Figure 5.10, Figure 5.11). This can be explained by the structural differences in the models and the way they consider uncertainty. The larger uncertainty in the PFA models propagates to the forecast and has a strong impact on the risk analysis (see hereafter).

*Evaluating catch options (example of the West Greenland Fishery)*

Differences in the demographic structure and in the way models handle uncertainty can result in strong differences in the risk analysis and evaluation of catch options (Figure 5.12).

For some of the North American stock-units, the probability to reach CL (here in total egg deposition) can differ a lot between the LCM and the PFA models. This is especially the case for the stock-units where the 1SW fish represent a high proportion of the egg deposition, such as Newfoundland for instance. In that case, the probability to reach CL is logically much higher in the LCM (Figure 5.12).

Probabilities to reach CL are more consistent between LCM and PFA models for European stock-units. Differences in the way the models handle uncertainty can explain some of the differences. For example, for Ireland (Figure 5.12), the probability to reach the CL calculated from the PFA models is higher than with the LCM. Both PFA and LCM predict the same average eggs abundance which is below the CL. The difference in the probability to reach CL results from the fact that the LCM generates more precise posterior distributions (lower uncertainty), which logically results in a lower probability to reach the CL. Also, important differences exist for Norway and Russia stocks between PFA and LCM. Those differences can be explained by the fact that in the LCM the risk analysis is carried out for all stock-units constituting Norway (NO.MI, NO.NO, NO.SE, NO.SW) and Russia (RU.AK, RU.KB; RU.KW, RU.RP) by summing *a posteriori* the abundances of egg deposition. By contrast, in PFA models, the risk analysis is conducted from aggregated data, where the calculated productivity is the aggregated productivity of a given stock-unit.

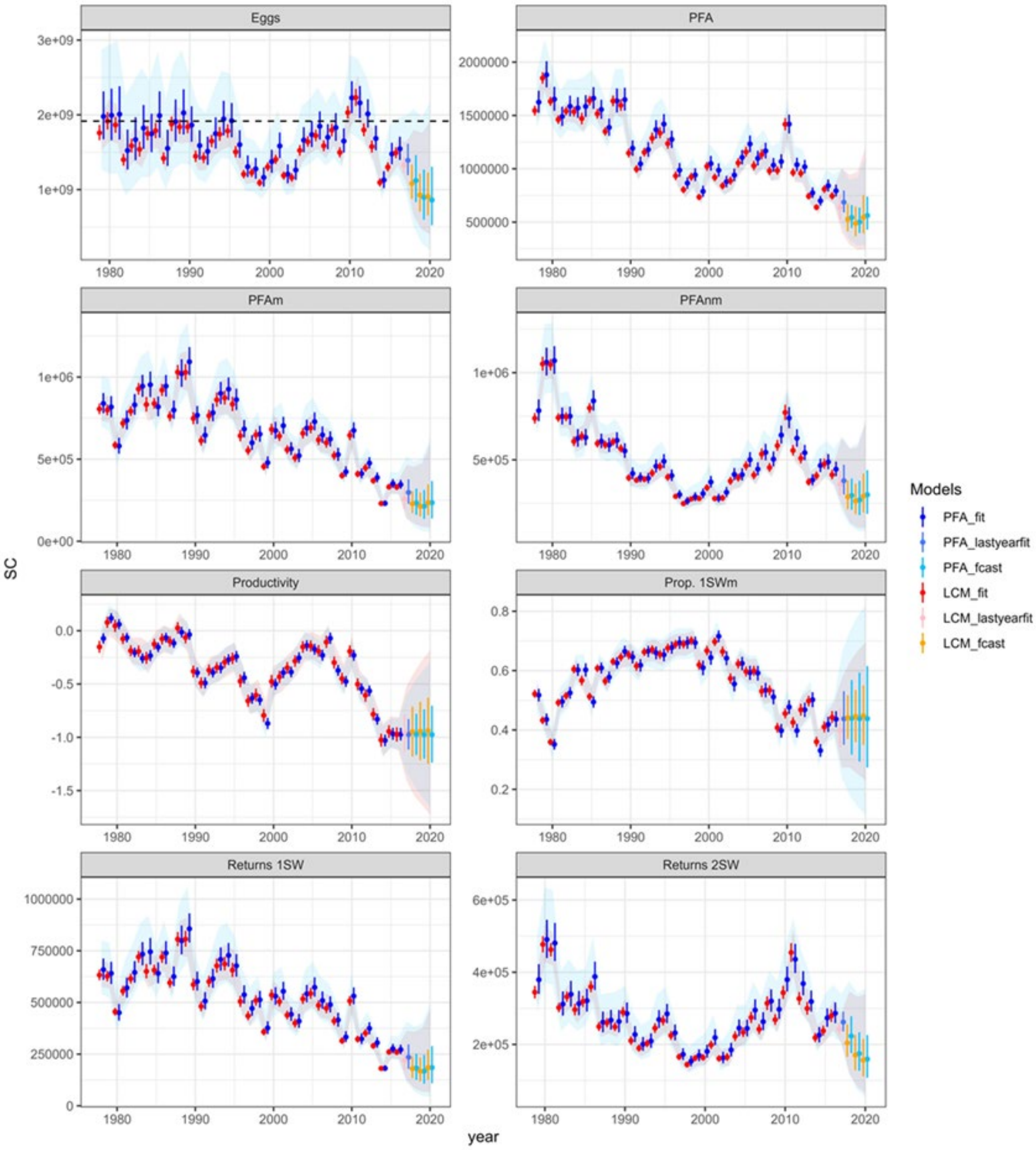


**Figure 5.8. UK – Scotland - Probability distributions of the number of eggs potentially spawned, PFA (total PFAm + PFAnm), PFA maturing (PFAm), PFA non-maturing (PFAnm), productivity, proportion of fish maturing as 1SW, returns 1SW and returns (MSW). Thick points represent the median and whiskers represent the 95% posterior credible interval. Blue: PFA model; Red: Life cycle model (LCM); Dark colour: historical time series; Light colours: Forecasted years (under the scenario of no catches at West Greenland and Faroes).**

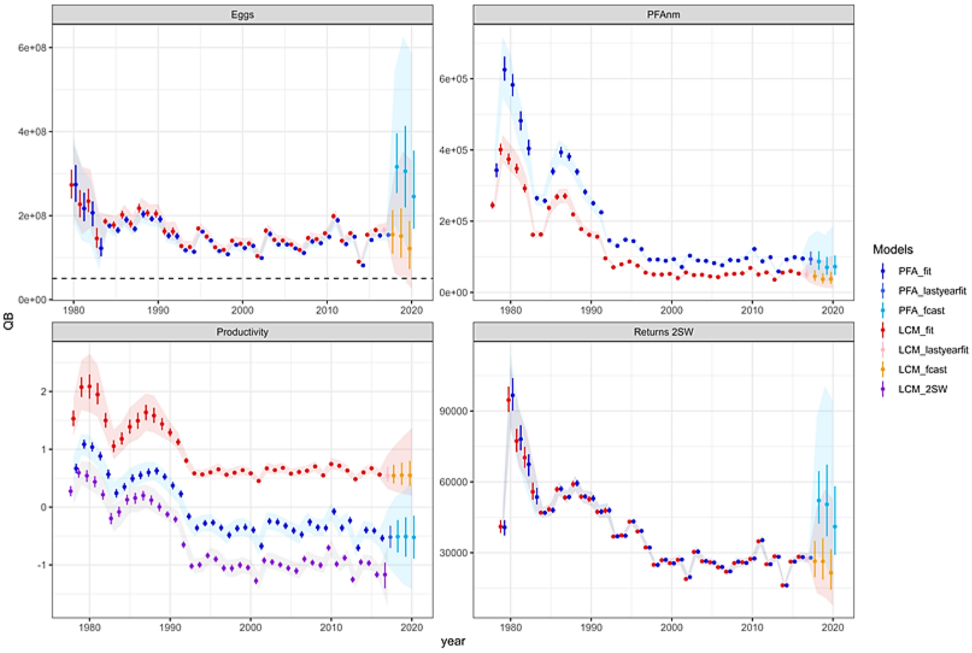


**Figure 5.9. Quebec - Probability distributions of MSW Productivity, the number of egg potentially spawned by MSW fish, MSW returns and PFAnm for Quebec region. Thick points represent the median and whiskers represent the 95% posterior credible interval. Blue: PFA model; Red: Life cycle model (LCM); Dark colour: historical time series; Light colours: Forecasted years (under the scenario of no catches at West Greenland).**

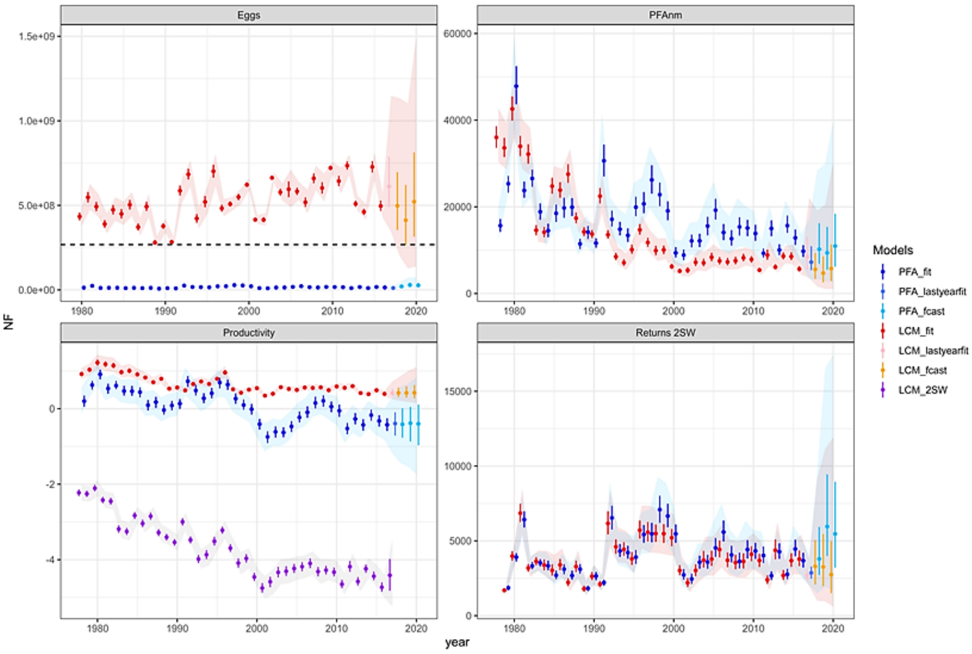


**Figure 5.10. Newfoundland - Probability distributions of MSW Productivity, the number of egg potentially spawned by MSW fish, MSW Returns and PFAnm for Newfoundland region. Thick points represent the median and line represent the 95% posterior credible interval. Blue: PFA model; Red: Life cycle model (LCM); Dark colour: historical time series; Light colours: Forecasted years (under the scenario of no catches at West Greenland).**

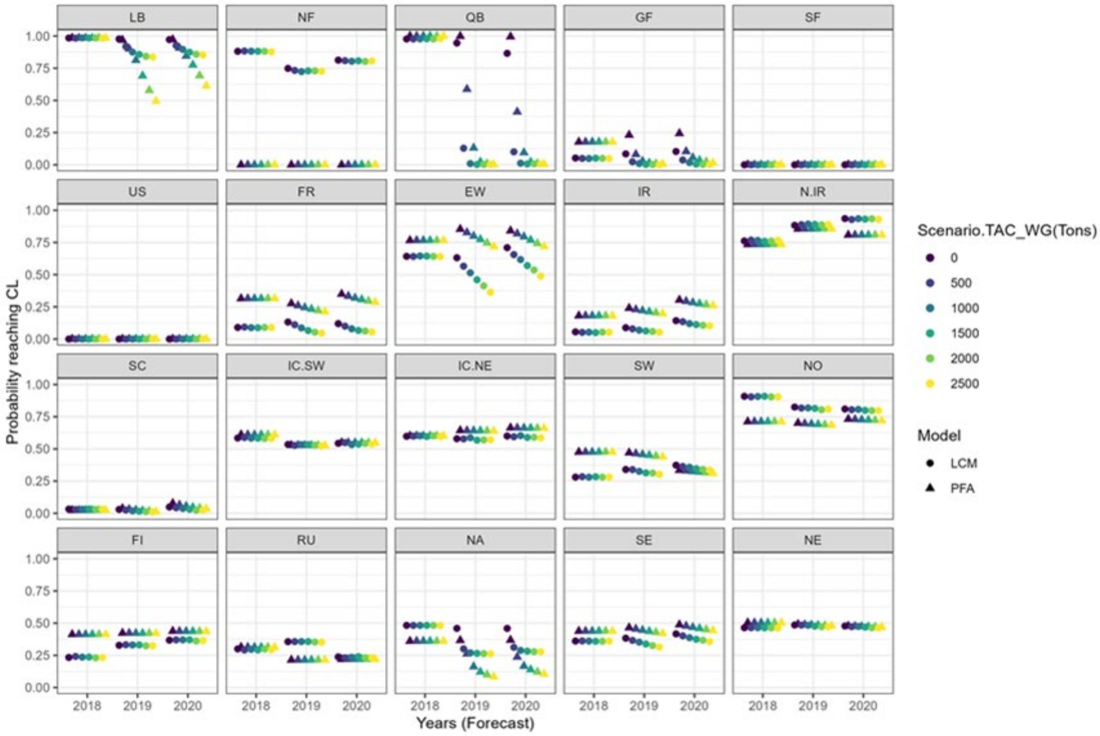


**Figure 5.11. West Greenland catch options. Probability to reach Conservation Limits obtained under different catches options at West Greenland. Catch options: 0, 500, 1000, 1500, 2000 and 2500 tons (3 years projections). (LB, NF, QB, GF, SF, US) North America; (EW, IR, N.IR, SC, IC.SW) Southern Europe; (IC.NE, SW, NO, FI, RU) Northern Europe. Panels (NAC, NEAC-S, NEAC-N) give probabilities to simultaneously achieving the management objectives for all stock-units of NA - North America (NAC), SE - Southern Europe (NEAC-S) and NE - Northern Europe (NEAC-N). Models: circle=Life cycle model (LCM), triangle= PFA.**

# 6 Transparent Assessment Framework (TAF)

In accordance with ICES transparent assessment framework (TAF) policy, it was agreed to use GitHub as the standard tool for code repositories and to use ICES GitHub accounts to open these repositories (ICES contact - Cecilia Kvaavik, <cecilia.kvaavik@ices.dk>).

A Data ToolBox has been produced by the 'discardless' project to provide online data review tools. Further details in WD: Hernvann *et al.* (2023)

| URL | Purpose: Data ToolBox |
|---|---|
| https://sirs.agrocampus-ouest.fr/discardless_app/WGNAS-ToolBox/ | Repository for data call contributions |

R-codes for the run reconstructions and for the LCM are independent. Having just one repository for all the different codes would make it difficult to create and manipulate branches independently for each project. To make things more flexible, it was agreed to set up six different independent repositories.

- One repository has been set up under the ICES Expert Group (ices-eg) GitHub account. This repository is used as the main WGNAS repository for data call contribution, which is the current practice for most of the stock assessment groups.

| URL | Purpose: |
|---|---|
| https://github.com/ices-eg/wg_WGNAS | Repository for data call contributions |

- Five separate repositories have been set up under the ICES Transparent Assessment Framework (ices-taf) GitHub account were all ICES stock assessment work happens. These repositories will be used to deposit model codes.

| URL | R code for: |
|---|---|
| https://github.com/ices-taf/wgnas-lcm | Life Cycle Model |
| https://github.com/ices-taf/wgnas-rr-neac | run reconstruction model, NEAC |
| https://github.com/ices-taf/wgnas-rr-nac | run reconstruction model, NAC |
| https://github.com/ices-taf/wgnas-pfa-neac | PFA forecasting, NEAC (will not be developed after 2024) |
| https://github.com/ices-taf/wgnas-pfa-nac | PFA forecasting, NAC (will not be developed after 2024) |

Following discussions with WGNAS, these five repositories have been set up with the following configurations (read more about team permissions here: https://docs.github.com/articles/what-are-the-different-access-permissions)

- These repositories are not public.
- Only WGNAS member can access (read only) the codes.

- People included in a restricted list (the "WGNAS_Subgroup") are listed as contributors, meaning they have the read and write access (commit/push/pull) so they can actively contribute. The "WGNAS_Subgroup" has 7 members (Stephen Gregory, Rémi Lemaire-Patin, Geir H. Bolstad, Hugo Maxwell, Etienne Rivot, James Ounsley, Jonathan Gillson), but this list can be easily updated on request (View "WGNAS_Subgroup": https://github.com/orgs/ices-taf/teams/wgnas_subgroup). Any additional member should first link their GitHub user account with the ICES user account, this can be done here: https://taf.ices.dk/github/Identity/Account/login

# 7 Review

## 7.1 Reviewers' Report

We find the data and modelling approach used in the Life Cycle Model (LCM) appropriate for providing scientific advice on North Atlantic Salmon to NASCO. The data used and resulting estimates are consistent with the previous modelling approach, while the LCM improves upon the previous modelling approach. The LCM provides a consistent and integrated approach for all three commission areas. It matches the management needs and population dynamics of North Atlantic Salmon while producing fits to the observations using a scientifically sound approach. The working group has invested considerably in the data pipeline to provide timely and consistent data to the LCM, which can now be run for all three commission areas at once. This allows covariances among parameters to be better tracked and monitored and provides the basis for future research into environmental factors impacting salmon throughout the North Atlantic Ocean. The model is well documented at the theoretical and implementation level and the web page summarizing results allows easy comparisons across commission areas and stock-units. We elaborate on these positive features of the new approach below and then provide a number of recommendations for future development of the model.

We find the LCM to be an impressive step forward in the assessment of Atlantic salmon in the North Atlantic Ocean. The WGNAS has invested considerable time and effort to create the LCM over the past years and it is great to see the completion of this project and used for pro-duction management advice. The LCM provides a single, comprehensive model to estimate the abundance of salmon at different life stages across many stock-units. It relies on the same data and general approach as the previously used Pre-Fishery Abundance (PFA) models, but unites the data collection and analysis into a common framework. Comparisons across commission areas from the LCM are much easier than from the PFA due to this common framework. The single framework also allows estimation of covariances among stock-units that were not possible in the PFA, presenting an opportunity for future research on environmental conditions that could help explain these covariances and sharing of information across stock-units where data may have previously limited parameter estimation.

The documentation of the LCM was excellent. The theoretical basis of the LCM and comparison to the PFA were well described in the working papers "A hierarchical Bayesian life cycle model for Atlantic salmon stock assessment and provision of catch advice at the North Atlantic basin scale" and "Benchmarking the north atlantic salmon stock assessment: a new life cycle model to evaluate salmon mixed stock status and fisheries management scenarios across the north atlantic basin." Both provided technical descriptions of how the LCM works, where it differs from the PFA and comparison of important model output between the LCM and PFA. The web tool for examining output of the LCM is described in "WGNAS-SalmoGlob ToolBox: a web application for supporting Atlantic salmon stock assessment at the North Atlantic basin scale." We found the web viewer particularly useful for exploring LCM output and improving our understanding of how the model works. In addition, the LCM code was made available and was better commented than most code we have previously examined. The attention paid to documentation greatly facilitated this review.

The pipeline approach to entering data and running the model makes it easy to see how the data are used and estimates produced. One of us (Grant) was able to run the model with a different MCMC approach during the meeting, indicating how easy it is for non-developers to run the model. This is an important feature for working groups such as WGNAS to prevent single point of failure problems that can occur when only one or a small number of individuals can run the model. The approach also supports changing data as new information becomes available, as was demonstrated during the review meeting when new genetic information was used to update the Faroes fishery catch data stream and country-specific conservation limits were reviewed and updated.

We found the LCM to be scientifically sound for providing catch advice to NASCO. The LCM more clearly handles the multistock catch of salmon in the West Greenland and Faroes fisheries than the PFA and has the ability to become more refined as improved understanding of the components of the catch become available. The LCM is able to fit the observations well using a common framework that lends itself to robustness checks, such as changes in marine natural mortality rates, or alternative hypotheses about time-varying parameters. The Bayesian estimation approach is well suited for the uncertain data that drives the LCM and the statistical fitting follows standard practices. Despite the many recommendations made below for future improvement, we feel the LCM is an appropriate tool for providing mixed-stock catch advice and is a step forward in model-based management advice used by the working group.

## 7.2 Reviewers' Recommendations

We recommend further additions in terms of diagnostics, analytical approaches and management recommendations to improve both the modelling approach and management advice provided by the working group. We prioritize them based on their perceived level of importance and ease of incorporation.

High priority:

1. We recommend the authors use the nimbleHMC algorithm for estimation rather than the default Metropolis-Hastings/Gibbs MCMC algorithm used currently. The HMC algorithm will improve the speed in which the MCMC algorithm reaches a sufficient effective number of sample sizes and the ability to efficiently explore the posterior distribution of the model. The implementation of the HMC MCMC algorithm is relatively straightforward, as demonstrated in the benchmark and will allow the WGNAS to run models quickly during meetings. In the 2_compile_model.R script the "configureMCMC" function can be exchanged for "configureHMC" on line 84 and "buildDerivs = TRUE" added to the "nimbleModel" function call on line 49. Having 1100 iterations, with 10 thin and 500 burnin across 10 parallel chains ran in ~16 hours on a personal computer with greater level of convergence than illustrated in the benchmark (all Rhat < 1.01 and Neff > 10,000). The number of iterations could easily be reduced to ~300 to have the model run quicker and achieve >3,000 effective samples. In the long term, we recommend that authors transition the model to Stan because of the ability to optimize the model for sampling efficiency/speed and improved convergence diagnostics, but recognize that would take substantial effort and is not a priority.

2. We recommend the authors include figures of the prior predictive distributions of management quantities provided to NASCO (e.g. number of eggs/fish relative to conservation limits). While posterior distributions are currently included, adding the prior predictive distributions will allow managers and the working group to better understand how assumptions of the model impact management recommendations. Also, including figures of the prior and posterior distributions as density/histograms will better illustrate the distributions.

3. Similar to #2, we recommend the authors include the number of effective samples for the posterior distributions of management quantities provided to NASCO. All the diagnostics currently included are for quantities that are not necessarily used for

decision making and, ideally, the working group should ensure that the posterior distribution of management quantities is well described by the MCMC sampler.

4. We recommend to include sensitivity analyses with the final model demonstrating robustness of the model recommendations to assumed values in the model (e.g. $M$). While the Bayesian and management framework allows uncertainty in parameters to be integrated into management advice, some fixed parameters and structural assumptions will impact management advice. These are standard in most stock assessments and will better allow the working group and managers to understand the sensitivities of model output to the different assumptions used. This will also help the working group prioritize research efforts to better address where model assumptions produce the least robust advice.

5. We recommend that the authors conduct within-model retrospective analysis on final models for each assessment/benchmark year. Retrospective analysis is a standard assessment diagnostic (see Carvahlo *et al.,* 2021) to evaluate the consistency of model based management advice to new data and identify if the model is producing poor management advice. Years of data are sequentially removed and the model is refit and mean relative error of key model outputs (i.e. median #eggs/fish relative to conservation limits) is calculated relative to the model with the full set of data. While it is unlikely feasible given the long convergence times, the significance of retrospective patterns could be evaluated using a simulation or bootstrap approach (see Breivik *et al.,* 2023).

6. We recommend that the working group stop using the approach inflating the SD of the sampling error associated with mean fish weight in the West Greenland catch for increasing the uncertainty in the numbers of fish caught. This is less intuitive and will be harder for subsequent researchers to reproduce. The working group should use SE of the mean instead. However, because the resulting uncertainty associated with catches is lower than desired using the SE, we recommend the working group use the mean weight and apply a default 5% CV for catch in numbers until better information is available.

Medium priority:

1. Similar to #3 above, the current assumption of constant marine mortality rate of 3% per month is almost certainly wrong but needed to allow the model to converge. We recommend the working group explore constraints on both smolt to PFA survival and probability of maturing along with marine mortality to see if this allows estimation of marine mortality.

2. We recommend that the working group include catch and return data from run reconstruction models assuming a multivariate distribution when incorporating the data into the LCM. The returns and catch data from the run reconstruction models have correlated errors because they are derived from the same model/parameters and the assumption of IID errors is not met. This will lead to under-estimation of uncertainty in management quantities. Catch and return data could be input as vectors with the variance covariance matrix input as a matrix and the distributions altered from univariate lognormal to multivariate lognormal.

3. We recommend the authors conduct retrospective skill determination for alternative forecast parameterizations of the LCM. Currently there are a number of model assumptions used in the forecast model (e.g. random walk for survival, maturity and five-year average of the proportion of NAC vs NEAC fish) that could potentially be outperformed by alternatives parameterizations (e.g. AR). Ultimately, conducting a retrospective forecast skill assessment could evaluate what forecast parameterization

performs the best. We recognize the long run times of the model make this recommendation challenging, it would require work intersessional to complete.

4. We recommend the authors' simulation test (self test) the model to ensure that all management quantities can be reliably estimated from the model and that there are sufficient data to estimate the model parameters.
5. We recommend the working group examine genetic data of West Greenland catch to see if the current assumption of constant harvest rate by stock-unit is justified or needs to be changed. These comparisons will need to recognize both the uncertainty in the current model estimates as well as the uncertainty in the genetic data.
6. We recommend that the working group continues labelling the results of LCM as 2SW despite data being provided as MSW and recommend the working group explore the implications of alternative life histories and the impact on management advice in the LCM. This caveat should be described in the assessment document.
7. We recommend the working group include sensitivities that have density dependence in the LCM to allow internal calculation of reference points if NASCO is interested and explore the consequences of density dependence for achieving conservation limits. Having a model-based estimation of conservation limits would be a large change from current practice and would need the agreement from NASCO before use in catch advice.
8. We recommend that the working group include Denmark, Portugal and other stock-units in LCM when data are available.
9. We recommend that the author's account for the proportion of NAC fish caught in Faroes fishery in LCM hind- and forecast. Currently, the probability of achieving conservation limits for NAC stock-units is independent of catch in the Faroes. However, a small proportion of NAC fish are present in the fishery and not accounting for the extraction of NAC fish may overestimate the status of NAC stock-units relative to conservation limits under alternative catch scenarios.
10. We recommend that NASCO and the working group clarify the management scenarios used for the forecast in the assessment. Currently it is not clear if forecasts include scenarios where there are both catches at Faroes and West Greenland at the same time. The forecasts also do not account for home water fisheries where fish are easily allocated to stock-unit, which limits potential management advice. Recommend clarification from NASCO on allocation of TAC to homewater and Faroes fisheries and forecast under multiple allocation scenarios.
11. We recommend the working group improve the model diagnostic figures so that breaks do not appear. For example, the number of effective samples plots suggest an error in the code.
12. We recommend that the working group coordinates with NASCO to ensure consistency between conservation limits and how eggs or fish are derived in the LCM. In addition, we recommend that the working group output the median and 95% CI of conservation limits in both eggs and fish.

Low priority:

1. We recommend the authors move the prior distributions of variance-covariance matrices used in multivariate normal distributions to the LKJ distribution via "dlkj_corr_cholesky" as it will likely increase sampling efficiency and speed over the inverse Wishart (sensu Nimble and Stan guides).

2. We recommend the authors modify the LCM to allow a single value of Russian catch to be used in LCM instead of estimating stock-specific values. Alternatively, the working group can account for the correlation of Russian data post 2021 in the likelihood function of the LCM when doing the variance inflation because an increase in catch in one river would be associated with a decrease in the catch in other rivers. As is currently specified, the variance inflation in the model will include catches beyond those observed (*i.e.* draws will invariably include catches from the upper end of the IID distributions across all Russian stock-units).
3. We recommend the working group continue to explore how catch and release fishing can best be accommodated within the LCM.

We thank the WGNAS working group, particularly chair Jonathan White and lead LCM developer Etienne Rivot, for their helpful discussions during the review. All members of the working group provided insight that was valuable and helpful during the review meeting. ICES staff, particularly Anne Cooper, ensured the meeting ran smoothly despite the many online participants, including one of us. We greatly appreciate the thorough documentation made available to us prior to the meeting, along with the code to run the LCM. This greatly increased our understanding of the LCM and allowed for a more informed and detailed discussion and review. We look forward to seeing the development and application of the LCM in the future.

# 8 Recommendations/Issue List

The proposed LCM advances the previously used Pre-Fisheries Abundance (PFA) forecast models used and in its developed format is considered fit for purpose in providing future advice. During the benchmark a series of items were noted for future consideration. These recommendations are listed below and categorized according to perceived priority.

Priority levels:

High - Considered useful and should be developed and reviewed over the next two cycles.

Medium - Considered useful and while not pressing, should be given due focus and investigation as to best means of reviewing and implementing.

Low – Considered useful but not pressing.

| No. | Priority | Summary | Detail |
|---|---|---|---|
| 1 | High | Calculation units in numbers of fish or number of eggs | The choice of the fundamental calculation unit needs further consideration. While results and advice have to date been provided in numbers of fish and the calculation units have also been fish, there is argument to move to number of eggs. This is owing to fish having two classes “1SW” and “2SW/MSW”, while eggs have only one.<br><br>Difficulty comes in translating to advice, as numbers of eggs has less meaning to managers than numbers of fish.<br><br>Translations of Numbers of eggs to numbers of fish in each age class is an option, enabling calculations to be more transparent, translation to fish age classes to be simpler and ability to change according to biology, the relationships between numbers of eggs and numbers of fish age classes “1SW” and “2SW/MSW”. This however, may lead to confusion if changes are implemented with an apparent shift in not only fish numbers, but also the associated Reference Points (Spawner Escapement Reserves, (SERs) and Conservation Limits (CLs)).<br><br>Moving to egg numbers would require the Run Reconstruction to calculate CLs in egg numbers, for both fish sea-ages. Alternatively, provide a single CL in egg numbers, estimated of returns in egg equivalents and leave age splits to the fishery.<br><br>This needs further in-depth exploration and consideration of resulting advice and requirements of advice recipients/ managers. |
| 2 | High | Retrospective pattern diagnostics | Develop retrospective pattern diagnostics such as the Mohn’s diagnostics (Mohn, 1999) that are commonly investigated to validate fish stock assessment models. |
| 3 | Medium | Proportion of escapees | Salmon farm escapees are not explicitly considered in the LCM and may be included in the “returns” data.<br><br>Consideration needs to be given of how these could and should be accounted for and how this would be implemented in data submissions, Run Reconstructions LCM and presentation of results. |
| 4 | Medium | Classification of data streams:<br><br>Caught and retained<br><br>Catch and release | Data used to estimate returns at the stock unit level are being based upon retained catch, released catch and a combination of these practices with exploitation rates defined appropriately to the practices. There needs to be clear flagging of these information sources in data submissions. |

| No. | Priority | Summary | Detail |
|---|---|---|---|
| 5 | Medium | West Greenland unreported catch estimate | A West Greenland fishery unreported catch estimate of 10 tonnes has been implemented in the assessment framework for many years. This figure was introduced as an expert judgement estimate. Since which time, with changes in fishing regulations, allowable catch quotas and markets, the mechanisms, means, method and purpose of catch at West Greenland have changed. The 10 tonnes estimated unreported catch has however, not been updated. This figure needs consideration and review and parameterization to incorporate appropriate uncertainty levels, which may vary over the time series.<br><br>The value and relative uncertainty may be broken down into subcomponents based on available information. This includes but is not limited to, location of catch (West Greenland to East Greenland) and origin of catch both to NEAC/NAC regional levels and stock-units as tagging/genetics data support the delineation. |
| 6 | Medium | Assessment retrospective analyses | Retrospective analyses in stock assessment are becoming commonplace diagnostic/sensitivity analyses tools. Retrospective analysis run the assessment assuming, iteratively, one year less data, usually to -5 years of the current assessment data. Two approaches have been found to be informative in assessing the resulting 5 assessments:<br><br>plotting the 5 years “peels” of critical assessment outputs (commonly Spawning Stock Biomass, Fishing pressure and Recruitment) to inform if the assessment commonly adjusts up, or down, a variable with additional annual data.<br><br>Calculation of Mohn’s rho – the average relative bias of retrospective estimates. Values within 0.20 and -0.15 are considered acceptable.<br><br>See Mohn (1999), Brooks and Legault (2016), ICES (2018), ICES (2020).<br><br>Means of computing comparable average relative bias of retrospective estimates should be considered. Choice of variable to be tracked needs consideration and may include egg numbers, total PFA, PFA maturing, PFA non-maturing, productivity, proportion 1SW maturing, returns 1SW and returns 2SW by commission area or assessment unit.<br><br>Presently model run times prohibit such retrospective runs on a single computer framework. Parallel versions may be a means of circumventing this issue. |
| 7 | Medium | Implement a Danish stock-unit into the WGNAS assessment | Danish scientists to coordinate data formats and streams for a Danish stock-unit into the Run Reconstruction and LCM ready to implement in the near future. |
| 8 | Medium | Improve implementation uncertainty for Faroes and West Greenland catch splits | Splitting the catches at Faroes and West Greenland are based on genetic assignment of a limited sample of fish. The splitting should therefore carry uncertainty both due to sampling error (limited sample size) and uncertainty in the genetic assignment of individual fish. A method was developped to quantify uncertainty due to sampling for the Faroes fishery but not for West Greenland and uncertainty in the genetic assignment is ignored in both cases. In the LCM, uncertainty in the split is controlled by the shape parameter of the Dirichlet distribution, which now is arbitrarily set to 100. Developing an approach (and harmonizing it between Greenland and Faroes catch split) for quantifying uncertainty resulting from both sampling errors and genetic assignement errors and for carrying forward the uncertainty in the genetic data to the LCM implementation is recommendable. |
| 9 | Medium | Smolt age definitions | The allocation of smolts to different smolt-ages is deterministic using fixed (provided in the data) proportions of smolt ages.<br><br>Consider making this inter-annually variable and stochastic. |

| No. | Priority | Summary | Detail |
|---|---|---|---|
| 10 | Low | Implement spit of NAC/NEAC in LCM future development. | Fore forecasting, splits between NEAC and NAC catch at the Faroes were updated in the benchmark based on available genetics data to 6.3% NAC 1SW and 11.0% 2SW/MSW.<br><br>Development of using a Dirichlet distribution was suggested as an option for basing this and variability on, in the future. |
| 11 | Low | Model sea-age/ life style considerations | The LCM considers two fish sea-ages: “1SW” and “2SW/MSW”. This is appropriate as it accounts for the vast majority of life patterns. However, in northern Europe there is a higher prevalence of >2SW fish, while in Northern Canada not only a notable proportion of >2SW fish but repeat spawners, consecutive year repeat spawners, alternate year repeat spawners and spawning young fish having skipped migration are also detected.<br><br>Presently in the LCM these alternate life histories are compressed into the “2SW/MSW” age category. While theoretically, the LCM could be developed to incorporate alternative life histories, the resulting computations it would incorporate preclude it use owing to the resulting run times and assessment time-frame practicalities |

# 9 References


Anderson, E.C., Waples, R.S. and Kalinowski, S.T. 2008. An improved method for predicting the accuracy of genetic stock identification. Canadian Journal of Fisheries and Aquatic Sciences 65(7): 1475–1486.

Baum, E. 1995. Atlantic salmon Spawner Targets for USA Rivers. Working Paper 1995. ICES-West Greenland NAS.

Bradbury, I.R., Hamilton, L.C., Sheehan, T.F., Chaput, G., Robertson, M.J., Dempson, J.B., Reddin, D., Morris, V., King, T. and Bernatchez, L. 2016. Genetic mixed stock analysis disentangles spatial and temporal variation in composition of the West Greenland Atlantic Salmon fishery. ICES Journal of Marine Science. 73: 2311-2321.

Brooks, E. N. and Legault, C. M. 2016. Retrospective forecasting — evaluating performance of stock projections in New England groundfish stocks. Canadian Journal of Fisheries and Aquatic Sciences, 73, 935–950.

Chaput, G. 2012. Overview of the status of Atlantic salmon (*Salmo salar*) in the North Atlantic and trends in marine mortality. ICES J. Mar. Sci. 69, 1538–1548.

Gilbey, J., Wennevik, V., Bradbury, I. R., Fiske, P., Hansen, L. P., Jacobsen, J. A. and Potter T. 2017. Genetic stock identification of Atlantic salmon caught in the Faroese fishery. Fisheries Research 187: 110-119.

Gilbey, J., Coughlan, J., Wennevik, V., Prodöhl, P., Stevens, J. R., Garcia de Leaniz, C., Ensing, D., Cauwelier, E., Cherbonnel, C., Consuegra, S., Coulson, M. W., Cross, T. F., Crozier, W., Dillane, E., Ellis, J. S., García- Vázquez, E., Griffiths, A. M., Gudjonsson, S., Hindar, K., ... Verspoor, E. 2018. A microsatellite baseline for genetic stock identification of European Atlantic salmon (*Salmo salar* L.). ICES Journal of Marine Science, 75(2), 662–674.

Hernvann, P.-Y., Lemaire-Patin R., Guitton J., Olmos M., Etienne M.-P., Laobouyrie M., Bezier L., Rivot E. 2023. WGNAS-SalmoGlob ToolBox: a web application for supporting Atlantic salmon stock assessment at the North Atlantic basin scale. ICES WKBSalmon 2023, Working Paper, October 2023, 46 pp.

IASRB. 2013. International Atlantic Salmon Research Board. 2013. Report of the Thirteenth Meeting of the International Atlantic Salmon Research Board. SAG(14)5. Identification of Genetic Stock of Origin of European Atlantic Salmon Captured at West Greenland for the Years 2002-2012. 2 June 2014. Saint-Malo, France. https://salmonatsea.com/wp-content/uploads/2020/08/SAG_14_5.pdf

ICES. 2004. Report of the Working Group on North Atlantic Salmon. Halifax, Canada 29 March–8 April. ICES CM 2004/ACFM:20, 286 pp.

ICES. 2018. Guidelines for calculating Mohn's rho: Retrospective bias in assessment. Draft document version 7 (2018-04-03), available at the Expert Groups area on the ICES Sharepoint.

ICES. 2020. Workshop on Catch Forecast from Biased Assessments (WKFORBIAS; outputs from 2019 meeting). doi: 10.17895/ices.pub.5997*ICES Scientific Reports 2(28)*.

ICES. 2023. Working Group on North Atlantic Salmon (WGNAS). ICES Scientific Reports. 5:41. 477 pp. https://doi.org/10.17895/ices.pub.22743713

Lemaire-Patin, R. and Rivot, E. 2023. Bayesian life cycle model for Atlantic salmon stock assessment. User guide for the R/Nimble codes. ICES WKBSalmon 2023, Working Paper, October 2023, 10 pp.

Jeffery, N.W., Wringe, B.F., McBride, M., Hamilton, L.C., Stanley, R.R.E., Bernatchez, L., Bentzen, P., Beiko, R.G., Clément, M., Gilbey, J., Sheehan, T.F. and Bradbury, I.R. 2018. Range-wide regional assignment of Atlantic salmon (*Salmo salar*) using genome wide single-nucleotide polymorphisms. Fisheries Re-search, 206: 163–175.

King, T.L., W.B. Schill, B.A. Lubinsky, M.C. Smith, M.S. Eackles and R. Coleman, 1999. Microsatellite and mitochondrial DNA diversity in Atlantic salmon with emphasis on small coastal drainages of the Downeast and Midcoast of Maine. USGS-BRD-Leetown Science Center, Kearneysville, West Virginia.

King T.L., Kalinowski S.T., Schill W.B., Spidle A.P. and Lubinski B.A. 2001. Population struc-ture of Atlantic salmon (*Salmo salar* L.): a range-wide perspective from microsatellite DNA variation. Molecular Ecology 10: 807–821.

Lear, W.H. and E.J. Sandeman. 1980. Use of scale characters and discriminant functions for identifying continental origin of Atlantic salmon. Rapp. P.-V Réun. Cons. Int. Explor. Mer. 176: 68-75.

Mohn, R. 1999. The retrospective problem in sequential population analysis: An investigation using cod fishery and simulated data. *ICES Journal of Marine Science*, 56, 473–488.

Massiot-Granier, F., Prévost, E., Chaput, G., Potter, T., Smith, G., White, J., Mäntyniemi, S. and Rivot, E. 2014. Embedding stock assessment within an integrated hierarchical Bayesian life cycle modelling framework : An application to Atlantic salmon in the Northeast Atlantic. ICES Journal of Marine Science, 71(7), 1653-1670. https://doi.org/10.1093/icesjms/fst240

Metcalfe, N.B. and J.E. Thorpe. 1990. Determinants of geographic variation in the age of seawardmigrating salmon, Salmo salar. J. Animal Ecol. 59: 135-145.

Mohn, R. 1999. The retrospective problem in sequential population analysis: an investigation using cod fishery and simulated data. ICES J. Mar. Sci. 56(4): 473–488. doi:10.1006/jmsc.1999.0481.

NASCO. 2013. North Atlantic Salmon Conservation Organization. 2013 Report of the Thirtieth Annual Meeting of the North American Commission. NAC(13)4. Management Objectives for Atlantic Salmon in the United States. 4-7 June 2013. Drogneda, Ireland. [https://nasco.int/wp-content/uploads/2020/02/NAC134.pdf](https://nasco.int/wp-content/uploads/2020/02/NAC134.pdf)

Olmos, M., Massiot-Granier, F., Prévost, E., Chaput, G., Bradbury, I. R., Nevoux, M., and Rivot, E. (2019). Evidence for spatial coherence in time trends of marine life history traits of Atlantic salmon in the North Atlantic. Fish and Fisheries, 20(2), 322-342. https://doi.org/10.1111/faf.12345

Olmos, M., Payne, M. R., Nevoux, M., Prévost, E., Chaput, G., Du Pontavice, H., Guitton, J., Sheehan, T., Mills, K., and Rivot, E. (2020). Spatial synchrony in the response of a long range migratory species (*Salmo salar*) to climate change in the North Atlantic Ocean. Global Change Biology, 26(1319-1337). https://doi.org/10.1111/gcb.14913

Olmos, M., Lemaire-Patin, R., Hernvann, P-Y., Ounsley, J., Queroue, M., Bolstad, G., Fiske, P., Chaput, G., Prevost, E., Nevoux, M., Dauphin, G., Rivot, E. 2023. Benchmarking the north atlantic salmon stock assessment: a new life cycle model to evaluate salmon mixed stock status and fisheries management scenarios across the north Atlantic basin. ICES WKBSalmon 2023 Working Paper, October 2023, 92 pp.

O'Sullivan, R. J., Ozerov, M., Bolstad, G. H., Gilbey, J., Jacobsen, J. A., Erkinaro, J, Rikardsen, A. H., Hindar, H. and Aykanat, T. 2022. Genetic stock identification reveals greater use of an oceanic feeding ground around the Faroe Islands by multi-sea winter Atlantic salmon, with variation in use across reporting groups. ICES Journal of Marine Science 79(9): 2442-2452.

Pella, J.J. and T.L. Robertson. 1979. Assessment of composition of stock mixtures. Fish. Bull. 77: 387–398

Porter, T.R., Healey, M.C., O'Connell, M.F., Baum, E.T., Bielak, A.T. and Côté, Y. 1986. Implications of varying sea-age at maturity of Atlantic salmon (Salmo salar) on yield to the fisheries. In Salmonid age at maturity, pp. 110-117. D. J. Meerburg [ed.] Can. Spec. Publ. Fish. Aquat. Sci. 89. 118 pp.

Potter, T., Gilbey, J., Wennevik, V., Fiske, P. and Arge Jacobsen, J. 2015. Working Paper No. 2015/23 WGNAS. Estimation of the composition of the Faroes salmon catch based on the genetic analysis of historic scales.

Rago, P.J., Meerburg, D.J., Reddin, D.G., Chaput, G.J., Marshal, T.L., Dempson, B., Caron, F., Porter, T.R., Friedland, K.D. and Baum, E.T. 1993. A continental run reconstruction model for the non-maturing component of North American Atlantic salmon: analysis of fisheries in Greenland and Newfoundland Labrador, 1974–1991. ICES CM 1993/M: 24, 21 pp.

Reddin, D.G. 1986. Discrimination between Atlantic salmon (*Salmo salar* L.) of North American and European origin. J. Cons. Int. Explor. Mer, 43:50-58.

Reddin, D.G. and Friedland, K. 1999. A history of identification to continent of origin of Atlantic salmon (*Salmo salar* L.) at west Greenland, 1969–1997. Fisheries Research, 43: 221–235.

Reddin, D.G., D.E. Stansbury and P. Short. 1988. Continent of origin of Atlantic salmon (*Salmo salar* L.) at West Greenland. J. Cons. Int. Explor. Mer, 44:180-188.

Reddin, D.G., E. Verspoor and P.R. Downton. 1990. An integrated phenotypic and genotypic approach to the stock discrimination of Atlantic salmon. J. Cons. Int. Explor. Mer, 47:83-88.

Reddin, D.G., Dempson, J.B. and Amiro, P.G. 2006. Conservation Requirements for Atlantic salmon (*Salmo salar* L.) in Labrador rivers. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/071.

Reddin, D.G., Poole, R.J., Clarke, G. and Cochrane, N. 2010. Salmon rivers of Newfoundland and Labrador. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/046. iv + 24 p.

Rikardsen, A. H., Righton, D., Strøm, J. F., Thorstad, E. B., Gargan, P., Sheehan, T., Økland, F., Chittenden, C. M., Hedger, R. D., Næsje, T. F., Renkawitz, M., Sturlaugsson, J., Caballero, P., Baktoft, H., Davidsen, J. G., Halttunen, E., Wright, S., Finstad, B. and Aarestrup, K. 2021. Redefining the oceanic distribution of Atlantic salmon. Scientific Reports 11(1): 12266. https://doi.org/10.1038/s41598-021-91137-y

Rivot, E., Lemaire-Patin, R., Olmos, M., Chaput, G., Hernvann, P-Y. 2023. A hierarchical Bayesian life cycle model for Atlantic salmon stock assessment and provision of catch advice at the North Atlantic basin scale. ICES WKBSalmon 2023 Working Paper.

Sheehan, T.F., Legault, C.M., King, T.L. and Spidle, A.P. 2010. Probabilistic-based Genetic Assignment model (PGA): assignments to subcontinent of origin of the West Greenland Atlantic salmon harvest. ICES Journal of Marine Science, 67: 537–550.

USASAC. 2022. Annual Report of the U.S. Atlantic Salmon Assessment Committee. Report No. 34 - 2021 Activities. Virtual February 28 - March 2, 2022. 163 pp. https://doi.org/10.25923/y1k1-xh35

# Annex 1: List of participants and meeting attendance

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| Name | Institute | Country | Meeting 20–23 June | Meeting 23–27 Oct | Email |
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| Name | Institute | Country | Meeting | | Email |
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# Annex 2: Working Documents list


April, J., Bradbury, I., Breau, C., Chaput, G., Dauphin, G., Douglas, S., Hogan, D.,Kelly, N., Robertson, M., Sheehan, T. and Taylor, A. 2023. Draft revised stock annex for the North American Commission (NAC) of Atlantic salmon: data structure and methods used to define the stock-units, conservation limits, reconstruct returns and spawners to stock-units of eastern Canada. ICES WKSALMON October 23 – 27 2023

Chaput, G. 2023. Context of the Sharing Agreement ("Grazing Fee") for Atlantic Salmon Fisheries in the North Atlantic. ICES WKSALMON October 23 – 27 2023.

Chaput, G. and Prévost, É. 2023. Review of the Atlantic Salmon NAC Pre-Fishery Abundance (PFA) and Catch Advice Model for West Greenland. ICES WKSALMON October 23 – 27 2023.

Hernvann, P.-Y., Lemaire-Patin R., Guitton J., Olmos M., Etienne M.-P., Labouyrie M., Bezier L., Rivot E. 2023. WGNAS-SalmoGlob ToolBox: a web application for supporting Atlantic salmon stock assessment at the North Atlantic basin scale. ICES WKBSalmon 2023 Working Paper #XXX, October 2023, 40pp.

Lemaire-Patin, R., Rivot, E. 2023. Bayesian life cycle model for Atlantic salmon stock assessment. User guide for the R/Nimble codes. ICES WKBSalmon 2023, Working Paper XXX/XXX, October 2023, 10 pp.

Olmos, M., Lemaire-Patin, R., Hernvann, P-Y., Ounsley, J., Queroue, M., Bolstad, G., Fiske, P., Chaput, G., Prevost, E., Nevoux, M., Dauphin, G., Rivot, E. 2023. Benchmarking the north atlantic salmon stock assessment: a new life cycle model to evaluate salmon mixed stock status and fisheries management scenarios across the north atlantic basin. ICES WKBSalmon 2023 Working Paper #XXX, October 2023, 92 pp.

Ounsley, J., Rivot, E., Bolstad, G., Maxwell, H., Gillson, J., Walker, A. 2023. Annex 11 Data Deficiencies - Russian data. 06/04/2023.

Rivot, E., 2023. Advance_Benchmark_Priorities_WGNAS2023_TABLE. March – 2023.

Rivot, E. and Dubost, G. 2024. Life Cycle Model for Atlantic salmon stock assessment Retrospective analysis using Mohn's $\varrho$ statistics.

Rivot, E., Lemaire-Patin, R., Olmos, M., Chaput, G., Hernvann, P-Y. 2023. A hierarchical Bayesian life cycle model for Atlantic salmon stock assessment and provision of catch advice at the North Atlantic basin scale. ICES WKBSalmon 2023 Working Paper #XXX, October 2023, 145 pp.