Stock Annex: Herring (*Clupea harengus*) in subdivisions 25–29 and 32, excluding the Gulf of Riga (central Baltic Sea)

Stock-specific documentation of standard assessment procedures used by ICES.

Stock	Herring (*Clupea harengus*) in subdivisions 25–29 and 32, excluding the Gulf of Riga (central Baltic Sea) (her.27.25-2932)
Working Group	Working Group on Baltic Sea Fisheries (WGBFAS)
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Last revised by	-

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A. General

A.1. Stock definition

The stock comprises of several spring-spawning herring components and and smaller autumn-spawning components. Spring-spawning occurs at the coast with a temporal gradient from south to north. After spawning, individuals migrate to the deep basins for feeding. In addition, migrations between subareas of the Baltic have been observed (Aro, 1989). Since 2005, the stock has been managed together in units SD 25–27, 28.2, 29 and 32 (EC and Russian quotas). The current management unit consists of a number of smaller spawning components, some of which have been shown to be genetically distinct. Herring in different subdivisions differ in, among other things, growth, and sexual maturity (Popiel 1958, Ojaveer 1989, ICES 2023a), but to what extent this difference is reflecting genetic differences are not yet determined.Mixing between Central Baltic herring stock and the western Baltic spring spawning herring occurs, but stock identification and allocation of catches are currently not resolved. Analyses suggest a progressive genetic differentiation along the entire southern Baltic coasts from SD24 to SD26 rather than a clear-cut division between different assessment units. Stock mixing occurs also between the Central Baltic herring and the Gulf of Riga herring, but discrimination between these stocks is less problematic as they are distinguishable based on the body and otolith morphometrics and other biological features (ICES 2018).

A.2. Fishery

Pelagic stocks in the Baltic Proper (subdivisions 25–29, 32) are mainly taken in pelagic trawl fisheries, of which the majority take herring and sprat simultaneously. But coastal gill net, trap net, and purse-seine fisheries targeting herring for consumption also exist. The estimates of pelagic catch compositions are based on logbooks and landing declarations. Discarding at sea is not considered to be a problem for this stock. The major part of the catch is historically taken by Sweden, Poland, and Finland. Landings of central Baltic herring caught in the Gulf of Riga are included in the assessment.

A.3. Ecosystem aspects

Drastic changes in the weight-at-age (WAA) of herring have been observed since the late 1980s (Parmanne *et al*., 1994; Cardinale and Arrhenius, 2000; ICES, 2022). The low WAA has had dramatic effects on the biomass and the catches of herring. Additionally, the poor condition of the fish (i.e. low fat content) has important implications on the marketing for human consumption (Raid and Lankov, 1995).

Three different hypotheses have been put forward to explain the decrease in WAA of Baltic herring, which include (i) a reduction in selective predation of cod on smaller herring (Sparholt and Jensen, 1992; Beyer and Lassen, 1994), (ii) an influx of slow-growing individuals from the northern areas, and (iii) a real decrease in growth rates due to changes in stock size and feeding environment.

The latter hypothesis has been also supported by Flinkman *et al*. (1998) showing changes in WAA in the Northern Baltic to be related to the mesozooplankton species composition. For the Central Baltic, Horbowy (1997) modelled the growth of herring in relation to the biomass of *Mysis mixta*. Similarly, Szypula *et al*. (1997) stressed the importance of the macrozooplankton fraction in the diet of planktivores. Other studies have shown the importance of the copepod *Pseudocalanus* spp. for nutrition of Baltic herring (Davidyuka, 1996; Möllmann *et al*., 2003). Low salinity conditions have negatively affected the stock development of this copepod (Möllmann *et al*., 2003), which is the most important food item for open-sea herring in spring. The increased competition with the sprat stock has been indicated as another crucial factor in the decrease of herring growth, operating via top–down regulation and density-dependent mechanisms (Cardinale and Arrhenius, 2000; Casini *et al*., 2006).

B. Data

B.1. Commercial catch

Landings data are included as total landed weight (tonnes) and start in 1903, with 1903-1973 landings data obtained from the ICES historical database. Landing data from 1974 have been collected annually by the Baltic Fisheries Assessment Working Group and documented in the reports. The most recent landing data (from 2007) are available in the Inter Catch database. Allocations of the adjacent Central Baltic herring and Gulf of Riga herring landings in Subdivisions 28.1 (Gulf of Riga) and 28.2 (Baltic Proper) are conducted annually using estimated proportions of both stocks in the commercial catches. Previously, Denmark, Sweden, and Poland have been using fisheries-independent sampling to correct logbook-based estimates of the landings and account for the mixing of herring and sprat in trawl fisheries. In this fishery, the logbook data may not be sufficient and the sampling is used to increase the accuracy of the landing data.

Discards are considered negligible in the fishery for Central Baltic Herring.

B.2. Biological sampling

B.2.1. Weight at age

Weight-at-age in the stock (WEST) is assumed to be the same as weight-at-age in the catch (WECA). No survey information from the first quarter is available, which could be used as the mean weight in the stock. Analyses conducted during WKBBALTPEL (ICES 2023a) showed that WECA and WEST in quarter 4 generally show a high correlation. Differences, however, occur especially in ages 1 and 2 and for SDs in the southern Baltic Sea. WECA is distinctively larger than WEST for all age groups in SD 25 and 26.

B.2.2. Maturity

According to evidence of a spatial-temporal trend in maturation of herring stock, new analyses were conducted at the latest benchmark of central Baltic herring using data from 1984 to 2021 to produce a time-varying maturity at age matrix (ICES 2023a). Based on observations, and in line with previous analyses (ICES, 2013), maturity ogives are produced based only on the spring spawning part of stock using generalized linear mixed model. Maturity ogives are produced as predictions by area and year, and then averaged over the total area (by year) against the abundance in each SD as estimated by the BIAS survey, since the current stock assessment configuration do not allow results to be used by area, (ICES 2023a).

B.2.3. Natural mortality

The natural mortality used in the assessment of central Baltic herring varies between years and ages as an effect of cod predation and the life history of the species. Estimates of natural mortality (M = M1 + M2) of herring were obtained from a number of runs using the SMS models with alternative configurations of food intake by cod and alternative values of M1 (ICES 2023a). Values of M1 for herring was guided by analysis of growth. Specifically, length-at-age data from 1984 to 2021 were used to derive VB parameters (Linf , k and t0) to be used as input parameters to derive proxy of M1 to be used in SMS (ICES 2023a). Since length-at-age data reveals a decreasing trend all along the timeseries, the VB equation parameters per year were used as input value in the Barefoot Ecologist's Toolbox (http://barefootecologist.com.au/shiny_m) to produce a time-varying natural mortality vector. A significant breakpoint in the natural mortality time series was detected in 2000, so the mean value calculated before and after the breakpoint (M before 2000: 0.28, M after 2000: 0.38) were used to re-scale the assumed annual M1 in SMS from which (scenarios for "likely" M1 presented in WD1_MultiSpecies_M for the central Baltic herring her.27.25-2932 and Baltic sprat spr.27.22-32; ICES 2023a).

Thus, three alternative SMS configurations were selected based on AIC, which were M1_010 (average annual M1 = 0.1, Quarterly M1(1974-1999)=0.08/4 and M1(2000-2021)=0.12/4), M1_020_average annual M1 = 0.2, Quarterly M1(1974-1999)=0.17/4 and M1(2000-2021)=0.23/4 and lim_10 (10% quantile of the parameter a and b for food consumptions (ignoring correlation). M1_010 was used for the development of the different plausible reference model configurations while M1_010, M1_020 and lim_10 were used as alternative hypotheses of the M dimension of the ensemble. Natural mortality at age between 1903 and 1973 was assumed to be equal to the values estimated in 1974. This assumption is justified as M of herring is assumed to be dependent on the abundance of Eastern Baltic cod, for which the SSB was practically constant between the beginning of the century and 1974 (Eero et al., 2008).

Until the next SMS run is available an assumption of M needs to be made in the update assessments.

B 2.4. Length and age composition of landed and discarded fish in commercial fisheries

The The non-sampled catches are typically assumed to have the same age composition as those sampled in the same subdivision and quarter. The otolith-based age estimates are considered precise but further validation studies are needed to confirm their accuracy.

B.3. Surveys

For the assment of Central Baltic herring one abundance survey index is used. The index is estimated yearly and based on data from the internationally coordinated Baltic International Acoustic Survey (BIAS). The survey is conducted in autumn (October).

B.3.1. Survey design and analysis

The calculation of the survey index is conducted by the WGBIFS and provided to the WGBFAS in time for assessment.

B.3.2. Survey data used

WGBIFS provided in 20203 an updated tuning index for the assessment of the Central Baltic herring based on the BIAS herring abundance estimates in the ICES Subdivisions 25-29 per age-group (1-8+) for the years 1991-2021 (ICES 2023b). Compared to the previous tuning indices,used in assessment, some historic corrections were made. Finland presented corrections for their 2016, 2018 and 2019 survey results, which were implemented in the BIAS database. As result the herring abundance estimates changed very slightly for those years. WGBIFS recommends that, the updated and corrected BIAS index series can be used in the assessment of the Central Baltic herring stock with the restriction that the years 1993, 1995 and 1997 were excluded from the index series (ICES 2023b).

WGBIFS also provided a new Central Baltic herring tuning index in 2023, which also includes the survey data from the Gulf of Finland (SD 32) (ICES 2023c). WGBIFS recommended that, the alternative BIAS index series (including data from SD 32) could be tested during WKBBALTPEL the for the Central Baltic herring stock with the restriction that the years 1999, 2001-2005 and 2008 were excluded from the index series (ICES 2023a). The benchmark ended up accepting the new tuning index for the Central Baltic herring, resulting in an index that is shorter then what was used before, but now includes survey data from the Gulf of Finland,

Additionally, WGBIFS provided WKBBALTPEL also with a number of BIAS hauls and survey variance estimates per year for both index series, which are included in the assessment (ICES 2023a)

B.4. Summary of input data used in the assessment

Table 1. Herring (Clupea harengus) in subdivisions 25–29 and 32, excluding the Gulf of Riga (central Baltic Sea). Input data used in the Stock Synthesis assessment models.

Type	Description	Year range	Age range	Variable from year to year Yes/No
Catches	Catch in tonnes	1903–last data year	1–8+	No
Age compositions	Catch-at-age in numbers (thousands)	Commercial fleet: 1974–last data year Acoustic survey: 2000- last data year	1–8+ 1–8+	No
Weight at age	Empirical weight at age estimated from commercial data. Weight at age in stock = weight at age in catch	1974–last data year 1903-1973 assumed to be = 1974	1–8+	No
Maturity at age	Empirical maturity at age estimated from commercial data	1974–last data year 1903-1973 assumed to be = 1974	1–8+	Yes?
Natural mortality	Time varying natural mortality by age class for the entire time series derived from SMS (ICES 2023a)	1974–2021; 2022 =2021 1903-1973 assumed to be = 1974	1–8+	Yes (when a new SMS run is available)
Surveys indices	Abundance index from acoustic survey	Acoustic survey: 2000–last data year	1–8+	No

C. Assessment: data and method

C.1. Choice of stock assess model

During the 2022-2023 WKBBALTPEL, a novel assessment approach was presented for the central Baltic herring and accepted by the group (ICES, 2023a). As in the benchmark for northern shrimp in Skagerrak and the Norwegian Deep (ICES, 2022a) the approach is based on the Stock Synthesis assessment model (Version 3 (SS3), Methot and Wetzel, 2013). Stock Synthesis is designed to accommodate both age and size structures in the population (Methot and Wetzel, 2013). Three different SS3 models are considered for the central Baltic herring, each with its own age-varying naturality mortality rate. These three SS3 models are then incorporated in an ensemble model. In each case, the SS3 model is an age-based, single sex, single area, single fleet, and single survey model with a population comprised of 8+ age classes (with age 8 representing a plus group).

SS3 is programmed in the ADMB C++ software and is implemented in R using the r4ss (Taylor *et al.*, 2021) and ss3diags (Carvalho *et al.*, 2021) packages. SS3 searches for the set of parameter values that maximise the goodness-of-fit and then calculates the variance of these parameters using inverse Hessian and MCMC methods. Once the three SS3 models have been fitted, a series of interconnected diagnostic tests are run (Maunder *et al.*, 2020; Carvalho *et al.*, 2021; Kell *et al.*, 2021), and each model is assigned a weight based on its overall fit to the data (ICES, 2022a). Following this, a delta-Multivariate Log-Normal estimator (delta-MVLN; Walter and Winker, 2019; Winker *et al.*, 2019) is used to run the ensemble model. The delta-MVLN generates and stitches together the joint posterior distributions of the target derived quantities (e.g. SSB/SSB_{target} and F/F_{target}). These quantities are derived by using the delta-method to calculate asymptotic variance estimates from the inverted Hessian matrix of each SS3 model (i.e. the quantities are calculated from each of the three model runs). The delta-MVLN is used to run the ensemble because it can infer within-model uncertainty from maximum likelihood estimates (MLEs), standard errors (SEs) and the correlation of the untransformed quantities. Moreover, the delta-MVLN has been demonstrated to mimic the Markov Chain Monte Carlo (MCMC) approach closely (Winker *et al.*, 2019) and is therefore suitable for the task.

C.2. Model used for basis for advice

The assessment model used as the basis for advice for Central Baltic herring (*Clupea harengus*; CBH; her.27.25-2932) in subdivisions (SDs) 25-29, 32 excluding the Gulf of Riga (Central Baltic Sea) is the Stock Synthesis (SS) model (Methot & Wetzel 2013, Methot et al., 2022) fitted in an ensemble approach.

C.3. Assessment model configuration

All three SS3 models used in the ensemble share the same input data (summarized in Table 1) and model configurations (Table 2) with one exception. The models differ only in the natural mortality rates at age. The three models of CBH are age-based, single sex, single area, single fleet, and single survey models with a population comprised of 8+ age classes (with age 8 representing a plus group). Each model operates at a has a yearly time step with sexes combined (males and females are modelled together).

Input data:

- Landings data are included as total landed weight (tonnes) and starts in 1903, with 1903-1973 landings data obtained from the ICES historical database.
- Discards are considered negligible.
- An abundance survey index is estimated yearly from the internationally coordinated Baltic International Acoustic Survey (BIAS). The survey is conducted in autumn (October).
- Catch at age in numbers per year are included from the commercial fleet from 1974, the years and from the acoustic survey from 2000, excluding years 2001-2005 and 2008.

Population dynamics and model settings:

1. Each model has a yearly time step with combined sexes (males and females are modelled together).
2. Fishing mortality was modelled using a fleet-specific method (Methot *et al.*, 2021). The models assume an age-based selection pattern for the fishery (logistic) and that this selection pattern remains the same throughout the year. Option 5 was selected for the F report basis; this option corresponds to the fishing mortality requested by the ICES framework (i.e. simple unweighted average of the F of the age classes chosen to represent the F_{bar} (age 3-6)).
3. Natural mortality (M) is age- and time-varying and different M at age vectors are used in each of the three SS3 models.
4. Proportion mature at age is time varying and estimated from commercial catch data.
5. Weight at age of the stock and of the catch age is time varying and estimated from commercial catch data.
6. Fishery selectivity is assumed to be age-specific and time-invariant. For both commercial fleet and surveys, a random walk selectivity was used. This selectivity pattern provides for a random walk for ln(selectivity). The model assumes logistic selectivity for both the fleet and the survey for age 5 to 8+.
7. Recruitment is derived from a Beverton and Holt stock recruitment relationship (SRR) and is assumed to be a single event occurring at the beginning of the year. Variation in recruitment was estimated as deviations from the SRR. Recruitment deviates are estimated from 1974 to current year and for 1968 to 1983 as early recruitment deviates. Recruitment deviates are assumed to have a standard deviation (σR), where σR is the stochastic recruitment process error fixed at 0.5 in this model. The steepness (h) for the SRR and the autocorrelation of recruitment are also estimated by the model.
8. The model starts in 1903 and the age structure of the initial population was assumed to be in an exploited state. The initial catches of the commercial fleets were assumed to be the average of the first three years (1903-1905) with a fixed standard error of 0.2.

Samples sizes, CVs, data weighting:

9. The commercial catches in tonnes by year are assumed to have a standard error of 0.2 for the initial catches, 0.1 for catches in 1903-1973 and 0.05 for catches in 1974 to the last year of catch data.

10. The annual sample size associated with the age distribution data is reported as the number of trips sampled for commercial catches (as reported from national sources) and the number of hauls for the surveys.
11. The CV of the acoustic survey index was estimated through bootstrapping (ICES 2023b).
12. Dirichlet-multinomial error distribution was used as an additional weighting of the age compositions (Methot et al., 2022).

Recruitment estimated from the assessment:

13. The assessment model starts at age 0 and, hence, recruitment in the model refers to abundance of age 0 in the population.

Table 4. Central Baltic herring in subdivisions (SDs) 25-29, 32 excluding the Gulf of Riga (Central Baltic Sea). Settings of the Stock Synthesis *Reference_run_SD32_survey* model configuration. The table columns (left to right) show: the parameter name, the number of estimated parameters, the initial values (from which the numerical optimization is started), the intervals allowed for the parameters, the priors used (value and standard deviation), the value estimated by the model and its standard deviation. Parameters in bold are set and not estimated by the model. * indicates that the parameter is close to the bound.

Parameter	Number of parameters estimated	Initial value	Bounds (low,high)	Prior and standard deviation	Value (MLE)	Standard deviation
Natural mortality (age classes 0-8+)		Time varying derived from SMS 1903-1973 = values estimated in 1974.				
Stock and recruitment						
Ln(R_0)	1	17.76	(16, 25)	No_prior	17.18	0.067
Steepness (h)	1	0.74	(0.1, 1)	0.74 (0.113)	0.78	0.041
Recruitment variability (σ_R)		**0.50**				
Ln (Recruitment deviation): 1974 - 2020	47					
*Recruitment autocorrelation***	1	0	(0,1)		0.18	0.09
Initial catches		Average of 1903-1905				
Commercial fleet**	1	0.009	(0.001, 1)	No_prior	0.009*	0.002
Selectivity						
Commercial fleet						
Change from age2 to age3	1	0.79	(-5, 9)	No_prior	0.87	0.050
Change from age3 to age4	1	0.37	(-5, 9)	No_prior	0.39	0.050
Change from age4 to age5	1	0.19	(-5, 9)	No_prior	0.06	0.060

Change from age5 to age8+	1	0.09	(-5, 9)	No_prior	0.48	0.060
Acoustic Survey						
Change from age2 to age3	1	0.69	(-5, 9)	No_prior	0.50	0.08
Change from age3 to age4	1	0.50	(-5, 9)	No_prior	0.49	0.08
Change from age4 to age5	1	0.24	(-5, 9)	No_prior	0.08	0.09
Change from age5 to age8+	1	0.01	(-5, 9)	No_prior	0.26	0.10
Catchability						
Acoustic survey						
Ln(Q) – catchability		**-5.95741**				
Extra standard deviation	1	0	(0,1)	No_prior	0.156	0.050
Dirichlet-multinomial error distribution (Fleet)	1	5	(-5,5)	1.813 (6)	3.64	0.83
Dirichlet-multinomial error distribution (Acoustic survey)	1	5	(-5,5)	1.813 (6)	1.13	0.89

**Estimated and then fixed at the estimated value in the final *Reference_run_SD32_survey* model configuration used for the ensemble (ICES 2023a).

D. Short-Term Projection

The short-term projections were performed following the same procedures as set out by the benchmark (ICES, 2023a), with SS3 using the delta-multivariate log-normal (delta-MVLN) estimator (Walter and Winker, 2019; Winker et al., 2019) to provide stochastic forecasts with probabilities. Initial stock size: As estimated from the stock assessment; Recruitment at-age 0 is derived from stock-recruitment function with autocorrelation on recruitment.

Maturity-at-age is assumed as the average of the last three years in the assessment.

Weight-at-age is assumed as the average of the last three years in the assessment.

Natural mortality is assumed as the average of the last three years in the assessment.

Selection-at-age is constant, as in assessment.

Intermediate year assumptions: Based on assumptions about catch (TAC and any other appropriate considerations).

E. Medium-Term Projections

Not conducted for this stock.

F. Long-Term Projections

Not conducted for this stock.

G. Biological

B_{lim} was defined as 15% of B_0 (unexploited SSB at current conditions) at the latest benchmark (WKBBALTPEL, ICES, 2023a). The rest of the reference points were agreed during WGBFAS 2023 based on Management Strategy Evaluation runs (See Annex 6).

<table>
<tr><th>Framework</th><th>Reference point</th><th>Value</th><th>Technical basis</th><th>Source</th></tr>
<tr><td rowspan="2">MSY approach</td><td>MSY $B_{trigger}$</td><td>$B_{30\%}$</td><td>Relative value. Set B_0 x 30%. Determined through management strategy evaluation with the objective to achieve high sustainable yields without exceeding a 5% probability of SSB falling below B_{lim} in any single year.</td><td>ICES (2023a)</td></tr>
<tr><td>F_{MSY}</td><td>$F_{B30\%}$</td><td>Relative value. Set as the F which will achieve B0 x 30%. Determined through management strategy evaluation with the objective to achieve high sustainable yields without exceeding a 5% probability of SSB falling below B_{lim} in any single year.</td><td>ICES (2023a)</td></tr>
<tr><td rowspan="4">Precautionary approach</td><td>B_{lim}</td><td>0.15 x B_0</td><td>Relative value. Set at 15% of B_0.</td><td>ICES (2023a)</td></tr>
<tr><td>B_{pa}=MSY $B_{trigger}$</td><td>$B_{30\%}$</td><td>Relative value. Set B_0 x 30%. Determined through management strategy evaluation with the objective to achieve high sustainable yields without exceeding a 5% probability of SSB falling below B_{lim} in any single year.</td><td>ICES (2023a)</td></tr>
<tr><td>F_{lim}</td><td></td><td>Not available</td><td>ICES (2023a)</td></tr>
<tr><td>F_{pa}</td><td>$F_{B25\%}$*</td><td>F_{P05}. Relative value. Determined through management strategy evaluation. The F that leads to SSB ≥ B_{lim} with 95% probability.</td><td>ICES (2023a)</td></tr>
<tr><td rowspan="5">Management plan</td><td>MAP MSY $B_{trigger}$</td><td>$B_{30\%}$</td><td>MSY $B_{trigger}$</td><td>ICES (2023a)</td></tr>
<tr><td>MAP B_{lim}</td><td>0.15 x B_0</td><td>B_{lim}</td><td>ICES (2023a)</td></tr>
<tr><td>MAP F_{MSY}</td><td>$F_{B30\%}$</td><td>F_{MSY}</td><td>ICES (2023a)</td></tr>
<tr><td>MAP target range F_{lower}</td><td>$F_{B25\%}$*</td><td>Relative value. Calculated through a MSE, consistent with the ranges which result in no more than a 5% reduction in long-term yield compared to MSY.</td><td>ICES (2023a)</td></tr>
<tr><td>MAP target range F_{upper}</td><td>$F_{B40\%}$</td><td>Relative value. Calculated through a MSE, consistent with the ranges which result in no more than a 5% reduction in long-term yield compared to MSY. Capped to F_{P05}.</td><td>ICES (2023a)</td></tr>
</table>

* As determined from the MSE, to be precautionary this reference point can only be used with the MSY $B_{trigger}$

H. Other Issues

None.

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