Stock Annex: Northern shrimp (*Pandalus borealis*) in Division 4.a East and Subdivision 20 (northern North Sea in the Norwegian Deep and Skagerrak)

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

Stock: Northern shrimp

Working Group: Joint NAFO/ICES *Pandalus* Assessment Working Group (NIPAG)

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A. General

A.1. Stock definition

The populations of northern shrimp (*Pandalus borealis*) in the North Sea area including Skagerrak and the northernmost part of Kattegat are currently assumed to be distributed into three main stocks (ICES, 1990):

1) The Skagerrak and Norwegian Deep stock;
2) The Fladen Ground stock;
3) The Farn Deeps stock.

The *Pandalus* on the Fladen Ground and in Farn Deeps are recognised as separate stocks and management units on the basis of geographical separation, hydrographical considerations, and investigations on genetic stock structure (Knutsen *et al*., 2015). Up to 1990, the *Pandalus* in the Norwegian Deep and Skagerrak were also treated as two separate stocks for assessment purposes.

There is a continuous distribution of *Pandalus* from the Norwegian Deep (4.a East) into the Skagerrak and Kattegat, but often differences in size distribution between the two areas are recorded. Multivariate analyses of length distributions from the Fladen Ground, Norwegian Deep and Skagerrak indicated that the length–frequency distributions for these three areas were different. However, the differences between the Norwegian Deep and Skagerrak distributions were less pronounced than between either of these two and those from the Fladen Ground (ICES, 1989). Since 1990, *Pandalus* in the Norwegian Deep and Skagerrak have been considered one single stock.

A single stock assumption is supported by the genetics work of Knutsen *et al*. (2015), who showed that the stock in the Skagerrak and Norwegian Deep area comprises of one biological unit. Smaller, genetically different stocks were identified in some fjords along the Norwegian and Swedish Skagerrak coasts, but as the fishery on these shrimp units is comparatively small, these stocks are not managed or treated separately in the assessment. The only exception to this is *Pandalus* in the Gullmarfjord (Swedish west coast) which are managed on an *ad hoc* basis based on fishing days per year.

A.2. Fishery

The Skagerrak and Norwegian Deep shrimp stock is exploited by Denmark, Norway, and Sweden. The Norwegian and Swedish fisheries began around 1900, while the Danish fishery started in the early 1930s. The gears used in the fishery for northern shrimp are bottom trawls. Shrimp are landed both as boiled (on-board processing) and as raw with an approx. equal distribution between the two fractions within the total landings. Due to local demand, Swedish fishers generally have a higher proportion of shrimp landings as boiled (high value) shrimp, whereas the Danish fishers typically land a higher proportion of raw (smaller) shrimp as they are generally less quota-restricted. The proportions of raw and boiled shrimp in landings from the Norwegian fishery tend to lay between the Swedish and Danish proportions.

A.2.1. General description

Countries involved:

Denmark

Historically, the Danish *Pandalus* fishery has targeted both the shrimp stock in Skagerrak and Norwegian Deep as well as the stock on the Fladen Ground. In the period 1994 to 1999 the fisheries in these two areas were of about the same size, but since 2000 the Fladen fishery declined and came to a stop in 2004. Virtually no shrimp landings have been recorded from Fladen since 2004 and at present, all Danish shrimp landings come from Skagerrak and Norwegian Deep. Since 'at sea' boiled shrimp fetch better prices, an increasing number of Danish vessels now land boiled shrimp. In 2020 and 2021, around 1/3 of the landings were boiled, whereas in 2005 it was only around 12%. Most of the boiled shrimp are landed in Sweden. The majority of the Danish catches are, however, still landed in Danish fishing ports unprocessed. Most of these shrimps are landed directly to a few large factories processing almost all sizes of shrimp. The number of vessels participating in the *Pandalus* fishery has decreased from 191 vessels in 1987 to approx. ten vessels in 2020 and 2021. The vessels that have left the *Pandalus* fishery are the smaller ones, and the average vessel size has increased from 20 to 26 m in the period, while the average horsepower has increased from 415 to around 700.

Estimates of total shrimp discards from the Danish fishery based on on-board sampling of catches have been available since 2009. Annual discards of shrimp constitute around 3-5% of the catches. A higher discard rate is observed in some years, which is likely linked to high abundances of age 1 shrimp.

Norway

The Norwegian shrimp fishery is conducted by multi-purpose fishing vessels mainly trawling south of 59ºN. The total number of vessels in the fishery has decreased from

>400 in 1995 to 171 in 2021. Vessels in the length group <10.99 m dominate in terms of numbers, followed by vessels in the length group 11–14.99 m. The fleet has changed considerably since the mid-1990s. The number of trawlers <10 m has decreased, as has the number of vessels 11–20.99 m, while there has been an increase in vessels 10–10.99 m. A high number of small vessels (<15 m) operate in the Skagerrak, while the fleet in the west is more varied. The small vessels tend to fish along the coast, while the larger ones fish more offshore.

Approx. 50% of the Norwegian landings from Skagerrak are from vessels ≥15 m, whilst in the Norwegian Deep, approx. 80% of the landings come from vessels ≥15 m. Almost all catches are landed in ports along the Norwegian coast, with a small portion landed in Denmark and Sweden. In 2012–2021, boiled shrimp constituted approx. 50% and 60% of the landings from the Skagerrak and from the Norwegian Deep, respectively.

Despite the Norwegian discard ban (see below), shrimp are discarded by Norwegian fishers. Until 2016, estimates of Norwegian shrimp discards were based on Danish discard rates. Since 2017, discard estimates are based on data from the Norwegian Coastal Reference fleet (Hatlebrekke *et al.*, 2021; details later in the Stock Annex).

Sweden

At present, there are approx. 30 Swedish trawlers that can be considered specialised in shrimp fishing in the Skagerrak. The size of the vessels ranges between 12 and 35 m with an average of 22 m. Gross registered tonnage (GRT) varies from 18 to 343, with an average of 118 GRT. The average engine size is around 409 kW (92–738 kW). Larger trawlers generally operate in the eastern and central part of Skagerrak. In comparison, smaller trawlers mostly fish in the Swedish coastal zone inside a 'trawling border' where special regulations apply for the use of trawls: Trawling in these areas is restricted to waters deeper than 60 m and there are special restrictions to the length of ground rope and the size of the trawl and trawl doors.

In Sweden, there are two different markets for *Pandalus*, resulting in two different kinds of landings: a) higher value, larger sized shrimp sorted by a 10.5 mm sieve and boiled on board before landed, and b) lower value, smaller sized shrimp, sorted by a 8.5 mm sieve, landed fresh and sold to the industry for further processing. In recent years, approx. 50% of the landings have consisted of boiled shrimp.

In some years, the Swedish shrimp fishery has been constrained by the Swedish share of the TAC. This has affected discard behaviour, with fishers high grading their catches to increase the amount of higher-value boiled shrimp. In 2012, 2% of the Swedish shrimp trawls had a mesh size ≥45 mm; this increased to 41% in 2014, as fishers strove to increase size selectivity and capture larger shrimp.

On-board sampling and self-sampling of Swedish catches has taken place since 2008, with estimates of total discards ranging from 12% to 30% of the catch (Munch-Petersen *et al.*, 2013). Generally, on-board sampling is completed on shrimp trawls with grid OTB_CRU_32-69_0_0 and self-sampling on shrimp trawls with grid but no tunnel OTB_CRU_32-69_2_22. The discard data derived from on-board sampling is regarded to be of better quality than the data derived from self-sampling. However, on-board sampling may be influenced by observer effects.

A.2.2. Fishery management regulations

The shrimp fishery is regulated by a minimum mesh size in the codend (35 mm stretched), and by restrictions in the amount of landed bycatch. Since February 1st 2013 all shrimp trawls in the Skagerrak must be equipped with a species sorting Nordmøre grid with 19 mm bar spacing, and since January 1st 2015, the same regulation applies to the North Sea south of 62°N. Since January 1st 2016, a landing obligation applies for *Pandalus* in EU waters, and work is ongoing to improve the size selectivity of shrimp trawls, both by increasing mesh sizes and by developing size selective grids. Norway has had a discard ban for many years.

Norway is the only country that has a minimum legal catch size, which is 6.5 cm total length (15.0 mm CL). Shrimp landings can nonetheless contain up to 10 % undersized shrimp (in weight in the Skagerrak and in numbers in the Norwegian Deep). A Real-Time Closure system to restrict the fishing of undersized shrimp was implemented in Norwegian waters south of 62°N as of January 1st 2016.

A.3. Ecosystem aspects

Pandalus is an important prey species for many fish species in the North Sea and surrounding areas, including cod and saithe (Jørgensen *et al.*, 2014; Skorda, 2018).

The traditional trawls used in the shrimp fishery have small-meshed codends (35–45 mm), which means that a considerable amount of bycatch of fish is caught. According to the current EU regulations, the total amount of landed bycatch for human consumption (HC) should not exceed 50% (by weight) of the total landings from a single *Pandalus* fishing trip. Based on the available data on bycatch of HC species it is estimated that they currently constitute approx. 25% of the catches. The common HC species in the shrimp fishery include cod, haddock, anglerfish, saithe, and witch flounder. Deep-sea species such as lantern sharks, roundnose grenadier and greater silver smelt are also frequently caught as bycatch. Bycatch of commercial species is recorded in logbooks (Sweden and Denmark) or in the landings statistics (sales slips) (Norway). However, the bycatch of non-commercial, mainly discarded species is currently not recorded on a trip-by-trip basis. This type of bycatch is only registered for a very small proportion of the commercial trips that have an observer on board. In Norway, shrimp trawlers in the Coastal Reference fleet register all species that are caught, including all non-commercial, discarded fish species.

Mandatory fish selective grids, such as the commonly used Nordmøre grid (see above for information on its use in the fishery), significantly reduce the amount of bycatch that is caught by the shrimp fishery. Despite this, many shrimp fishers consider the HC fish bycatch to be a significant component of their catch and, when the TACs allow, it is legal to cover the grid-outlet with a netting tunnel (collecting bag) of 120 mm square mesh to allow for the retention of larger HC fish.

B. Data

B.1. Commercial catch

B.1.1. Landings data

B.1.1.1. Commercial landings

Commercial landings data for *Pandalus* are available (to NIPAG) from 1970 to present for Denmark, Sweden, and Norway. Landings are reported as total landed weight from each of the three countries spilt by area (3.a and 4.a East) and quarter. Since a significant amount of the landings consist of boiled shrimp, the official recorded landings of this catch component have been adjusted for weight loss due to boiling. The adjustment factor that is currently used is:

fresh weight = 1.13 * boiled weight.

B.1.1.2. Data coverage and quality

Since 1990, the landings data for *Pandalus* in 27.3.a4.a are mainly based on information from logbooks and sales slips, which in combination deliver high-confidence, full coverage landings data at the fishing-trip level and at the spatial resolution of an ICES rectangle. Before this period, data is based on national and ICES landings statistics, which have good quality and good overall coverage, however, they have a much coarser spatial (ICES division or sub-division) and temporal (annual) scale.

Since 2005, Norwegian landings data are available at the trip level and at the spatial resolution of an ICES rectangle. Norwegian data back to 1977 are available by month.

Swedish landings for all years, and Danish and Norwegian landings from 2002 and 2000, respectively, have been corrected for weight loss due to boiling. Danish vessels started to land boiled shrimp in small amounts in 2000. Unfortunately, no information exists on the fraction of boiled landings prior to 2000 for the Norwegian fleet.

Landings data split by area and quarter back to 1908 (Sweden and Norway) and 1940 (Denmark) were compiled and digitised as part of the 2021-2022 benchmark (ICES, 2022). However, the addition of historical catches (1908-1969) in the assessment provided no benefit in terms of model fit and therefore it was decided that the assessment of the stock would only consider landings data back to 1970.

B.1.2. Discards estimates

Estimates of total discards, based on on-board sampling, have been available from Sweden since 2008 and from Denmark since 2009. However, because Danish LFDs (Length Frequency Distributions) split into landings and discards have only been available since 2013, WKPRAWN (ICES, 2022) decided to only use Danish discards from 2013 to present.

Until 2015, no Norwegian observer data existed. However, in 2016 Norway initiated a sampling program (the Coastal Reference fleet) within which a selected number of shrimp vessels report all catches (including all discards). Since 2017 (too little data in 2016), Norwegian discard estimates are based on data from the Coastal Reference fleet.

For 2009–2016, Norwegian discards of *Pandalus* in the Skagerrak have been estimated by applying the Danish discards-to-landings ratio to the Norwegian landings. These estimated discards in the Skagerrak are likely to provide an underestimation, as the proportion of boiled shrimp in the Norwegian landings is larger than in the Danish landings. As there is minimal Danish observer data from the Norwegian Deep, there are no estimates of Norwegian discards from this area for 2009-2016.

In the stock assessment, landings (total landed weights) are used as input data in the model for all years until 2007, while total catches (landings + discards) are available and used in the assessment since 2008 for Sweden, 2009 for Norway, and 2013 for Denmark. LFDs are also used as input data and are provided as unsorted and sorted (landings + discards) catch based on data availability. In all cases, input data is split by area, quarter and fleet. The new assessment model introduced during the 2021-2022 benchmark estimates discards back in time based on discard ogives which are estimated by the model (ICES, 2022).

B.1.2.1. Data coverage and quality

Annual sample numbers and sample sizes are presented by country and quarter in the WKPRAWN 2022 benchmark report (ICES, 2022). The new assessment model introduced during the benchmark requires catch data (LFDs) from sorted catches to be spilt into landings and discards when available. The new assessment model is also capable of incorporating LFDs from unsorted catches.
Sorted catches for Sweden and Denmark are available from 2016 and 2013, respectively. Prior to this, data is provided by Sweden back to 1990 as unsorted catches.
Prior to 2018, the Norwegian sampling program of commercial catches has been based on the sampling of unsorted catches and therefore the data is provided in this format. Since 2018, data provided by Norway on numbers-at-length are based on data from the Coastal Reference fleet that sample sorted catches. Coverage by quarter and area of the Reference fleet is, however, not satisfactory, and a new sampling program that complements the Reference fleet needs to be established.

B.1.3. Recreational catches

There is no recreational fishery for *Pandalus*.

B.2. Biological sampling

B.2.1. Maturity

Pandalus is a protandric hermaphrodite, i.e., individuals are born as males and then become females. In the Skagerrak and Norwegian Deep, sex change takes place approximately at age 2 as a gradual process spanning late winter and early spring. During the 2021-2022 benchmark, it was decided that the Norwegian survey data (2006-present) would be used to estimate size at female maturity (ICES, 2022). The proportion of females at length was fitted to a logistic maturity curve, where mature females in quarter 1 (when the survey is conducted) are defined as all females contributing to the upcoming recruitment in quarter 2, i.e., berried females and females with roe already hatched.

B.2.2. Natural mortality

During the 2021-2022 benchmark, three different age-varying natural morality rates (M) were estimated for both sexes using the methods described in WD04 (ICES, 2022). Each of these M at age vectors are now implemented in the stock assessment, whereby each vector is considered to be a plausible scenario for natural mortality at age (ICES, 2022).

A fourth M scenario (i.e., time varying M) based on yearly predator abundances was presented to the benchmark, but is currently not implemented in the assessment of the stock.

B.2.3. Length and age composition of landed and discarded shrimp in commercial fisheries

Norwegian unsorted catches have been sampled on board by fishermen (self-sampling) and the Norwegian Coast Guard since 2006, and a time-series based on these LFDs are used as input data to the assessment. Vessels involved in the Coastal Reference fleet sample all catch components separately, including discards. A time-series of LFDs (spilt into landings and discards) based on the Reference fleet is used as input data to the assessment for all years since 2018 (data lacking from the Norwegian Deep for 2018-2019).

LFDs spilt into landed and discarded shrimp from the Swedish and Danish fisheries (data from on-board sampling) are provided from 2016 and 2013, respectively. In years prior, the Swedish LFDs are based on numbers-per-length from landings (1990-2007) or unsorted catches (2008-2015). LFDs based on unsorted Danish catches are available from 2009-2012 but are currently not included in the assessment.

All LFDs are spilt by quarter, area and fleet.

B.3. Surveys

Since 1984, a bottom-trawl survey for *Pandalus* in Skagerrak and the Norwegian Deep has been conducted annually by the Norwegian Institute of Marine Research. The survey has the objective of assessing the distribution, biomass, recruitment, and demographic composition of the shrimp stock, as well as the size of the stocks of shrimp predators and the measurement of hydrographical conditions in the distributional area of shrimp (Søvik and Thangstad, 2021). The survey data consist of four different time-series: 1) one time-series from October/November 1984–2002 using RV *Michael Sars* and the Campelen-trawl; 2) a point estimate for 2003 as RV *Michael Sars* was taken out of service and substituted with RV *Håkon Mosby*, whose winches at that time were not powerful enough for the Campelen trawl, resulting in the survey being conducted with a shrimp trawl; 3) a start of a potential new time-series as the survey in 2004 and 2005 was conducted in May/June with RV *Håkon Mosby* using the standard Campelen trawl; and 4) one time-series from January/February 2006 until present, using RV *Håkon Mosby* (2006-2016) and RV *Kristine Bonnevie* (since 2017) and the Campelen trawl. Conducting the survey in quarter 1 is expected to give a more reliable estimate of the 1-group abundance and the SSB (berried females) and was recommended by the ICES *Pandalus* working group in 2004 (ICES, 2005).

B.3.1. Survey design and analysis

The survey is stratified by four depth zones (100–200 m, 200–300 m, 300–500 m, and >500 m) and has a fixed station design. The survey design therefore assumes that the temporal variation in the shrimp stock generates the necessary randomness.

The trawl used is a Campelen 1800/35 bottom trawl with a rockhopper gear. Mesh size in the codend is 20 mm with a 10 mm inner lining net. Tow duration was 1 hour until 1989 when it was reduced to 0.5 hours. Tow speed is roughly 3 knots. No compensation for diurnal vertical migration is made. Strapping is used to ensure fixed trawl geometry (10 m rope 100 m in front of the doors).

A sample of approximately 300 shrimps is taken from each haul; the length of each shrimp is measured, and the sex and maturation stage is determined.

B.3.2. Survey data used

Input data to the assessment model from the survey is a time-series of total biomass and LFDs (abundance-at-length) by year and area.

Until 2021, a design-based survey index was used as input to the assessment, whereby the abundance-at-length was calculated as the mean density raised to the corresponding area and depth stratum within the survey strata system. Inconsistencies within the time series in coverage due to weather and technical issues required ad hoc corrections for missing strata and resulted in the removal of the entire 2016 survey from the previous survey index. In addition, the design-based approach was found to be sensitive to the stratified design due to the narrowness of the depth contours, as well as start- and stop-locations of trawl stations that sometimes crossed strata or area borders. Model-based survey standardizations that combine fixed effects (e.g. bottom depth) with random effects, and include information on spatio-temporal correlation have been shown to resolve such issues. The model described in Breivik *et al*. (2021) was specifically developed with the goal of improving the prediction of abundance-at-length data using spatial random fields and correlation between length groups. Consequently, the model of Breivik *et al*. (2021) was implemented to support the assessment of the stock.

The model was fitted to abundance-at-length data from the most recent section of the survey time series (2006-current year). The expected abundance-at-length is modelled as a Poisson distribution, with a length- and year-dependent intercept, a nonlinear depth effect, a latent mean zero Gaussian random haul effect with correlation structure across length within hauls, and spatio-temporal-length mean zero Gaussian random effects, as well as trawl distance as an offset. Length-dependent intercepts are linked through time using a random walk process to improve the estimation of rarely observed length groups. The correlation structures of the spatio-temporal random effects are further assumed to be stationary Matérn in space and with separate first order auto regressive (AR1) structures in both time and length. The latent haul effect accounts for an unexplained variation within each haul and includes an AR1 correlation structure in length. Only hauls located within the strata system are considered, and every three subsequent length groups are linked together for the estimation of latent effects to reduce the number of parameters and computational requirements. The spatial mesh was built using the triangulation method provided by R-INLA, using a minimum allowed distance between points of 30 km. Sensitivity tests showed that the selected configuration and mesh resolution were robust and provided an adequate balance between sufficient model complexity, stability and running time.

In addition to the LFD index, the assessment also considers a total biomass index. To ensure consistency in the methods used, total biomass is estimated using a spatio-temporal model implemented in sdmTMB package. This model mimics the model setup and configuration used for the length-based index with total observed density (catch weight per nautical square mile) as the response variable, as opposed to abundance-at-length. Comparing the split estimates of the old/new survey data with an estimate that uses the joint time series showed that a joint biomass index is preferable. This is because the mean estimates are very similar, however, the longer time series aids the parameter estimation and results in lower uncertainty especially in the new time-series.

Total abundance and associated uncertainty are predicted by area (Skagerrak and the Norwegian Deep). The resulting index follows largely the same trend as the design-based estimate with some notable deviations, particularly in years with coverage issues. Data from the 2016 survey are not included in the log-likelihood estimation and, thus, have no influence on the overall parameter estimates. However, abundance-at-length and uncertainty for 2016 are predicted from the model using the estimated fixed effects (bottom depth) and correlation structure. In contrast to the design-based index, the model-based approach enables the estimation of an index for 2016 that adequately reflects the associated uncertainty and, thus, provides better information of the abundance in 2016 than excluding the year entirely.

The stock indices for the two earlier time series (abundance-at-length), 1984-2002 and 2004-2005, are still design-based indices and are estimated in the software StoX (Johnsen *et al.*, 2019). Survey coverage was less of an issue when the survey was carried out in October/November, but in 2002, the northernmost stratum H1 was not covered.

B.4. Commercial cpue

Commercial standardised LPUE data are available by country (Denmark from 1987, Sweden from 1996, and Norway from 2000), but are not currently used in the assessment of the stock.

B.5. Other relevant data

C. Assessment methods and settings

C.1. Choice of stock assessment model

During the 2021-2022 benchmark, a novel assessment approach for northern shrimp in Skagerrak and the Norwegian Deep was presented and accepted by the group (ICES, 2022). As in the 2016 benchmark (Cardinale and Fernandez, 2016; ICES, 2016), the approach is based on the Stock Synthesis assessment model (Version 3 (SS3), Methot and Wetzel, 2013), however, in this case three different SS3 models are considered, 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 a two area (3.a and 4.a East), length-based model with a population comprised of 8+ age classes (with age 8 representing a plus group). Moreover, the modelled population is spilt into two sexes, with hermaphroditic individuals being born as males and changing to females later in life (protandrous hermaphroditism).

Stock Synthesis is designed to accommodate both age and size structures in the population (Methot and Wetzel, 2013). For northern shrimp, the numbers and LFDs from the fisheries and survey data are related to ages using the von Bertalanffy growth function. Each of the three SS3 models are run with a quarterly time step to account for the growth of individual shrimp throughout the year. The models all assume a length-based selection pattern for the fishery (logistic) and that this selection pattern remains the same throughout the year; thus, the shrimp become increasingly more selected as they grow throughout the year.

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, 2022). 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.

All three SS3 models share the following model configuration (see Table 1 for a summary of input and model settings):

<u>Input data:</u>

- Landings data are included as total landed weight (tonnes) spilt by area, quarter, and fleet.
- Discard data are included as total discarded weight (tonnes) spilt by area, quarter, and fleet.
- LFDs sampled from commercial catches are included as either sorted (landings + discards) or unsorted catch (just landings or total catch) based on data availability. All data on LFDs are spilt by area, quarter, and fleet.
- Survey indices are included as biomass by year and area. LFDs (numbers-at-length) from the survey are included by year, area, and sex.
- Survey data are available from 1984 to the last data year (excluding 2003), including the year in which the assessment is conducted (even if the catch data are not yet available for the year when the assessment is conducted). Due to changes in timing, the Norwegian survey is split into three different parts (1984–2002, 2004–2005 and 2006–present) and the average timing of

each period is assigned to each part (the month of year that the survey takes place is assumed to be 10.684, 5.776, and 1.912, respectively).

Population dynamics model and settings:

- Quarterly time-step. The model differentiates between sexes, with hermaphroditic individuals changing from males to females at approx. age 2. The model considers two areas (3.a and 4.a East) and 6 fleets (spilt by country and area). Lengths (i.e. carapace) 0 to 4 cm, in steps of 0.1 cm, are used to represent the population. Lengths 0.2 to 3.5 cm, in steps of 0.1 cm, are used for the input data.
- Fishing mortality was modelled using a fleet-specific method (Methot *et al.*, 2021). 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 1-3)).
- Lengths are related to ages (age classes 0 to 8+) assuming a von Bertalanffy growth function in the population model, with normally-distributed variability around the growth curve. Growth parameters (k, L_{inf}, t_0) and the CV of the normally-distributed variability are estimated by the model. There are two CV parameters: one for the youngest age and one for the oldest, with linear interpolation in between these ages.
- M is age-varying and different M at age vectors are used in each of the three SS3 models.
- Maturity parameters (L50 and K) were fixed across the two areas and derived externally from survey data. Length at maturity was described by a sigmoidal function with L50% set at 1.974 cm. More details are provided in WD09 (ICES, 2022).
- The weight-at-length (cm to kg) relationship is treated as a fixed input in the assessment, and is assumed to be constant over time, with parameters a=0.0016 and b=2.7532.
- Catchability and logistic selectivity-at-length curves are estimated separately for the survey in each area. These are assumed to be time invariant (i.e. catchability and selectivity within each area does not vary over time).
- A logistic selectivity-at-length, assuming no variation over time, is estimated for each of the commercial trawl fleets. The fishing mortality-at-length is the product of selectivity-at-length (normalized to have a maximum of 1) and the fleet-specific (year, quarter) fishing mortality parameters.
- 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 1984 to current year and for 1978 to 1983 as early recruitment deviates. Recruitment deviates are assumed to have a standard deviation (σR), where σR is the stochastic recruitment process error and is estimated by the model. The steepness (h) for the SRR and the autocorrelation of recruitment are also estimated by the model.
- The model starts in 1970 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 preceding five years (1965-1969) with a fixed standard error of 0.2.

Likelihoods of observed data:

- The ln(commercial catches in tonnes, by quarter and area) are assumed to have a standard error of 0.2. The catch for the year in which the stock assessment is conducted (e.g. the 2022 catch for an assessment conducted in 2022) is typically not available. In order to include the survey index from that year in the assessment, it was decided that the survey index would be manually moved to 31st December of the previous year. The survey is then moved back to its usual time (Jan/Feb) when estimating the advised (preliminary) TAC for the following year (e.g. the 2023 TAC for an assessment conducted in 2022).
- The observed ln(survey indices) by area are assumed to follow Normal distributions. The CV for each year and area is estimated using a spatio-temporal model (see section B.3.2 for more details).
- SS3 assumes multinomial likelihoods for the LFDs for catches and survey data. Sample sizes (by area and quarter) are reported as the number of hauls for the survey and as the number of trips for the commercial fleets.

Calculation of an annual F_{bar}:

- F_{bar} is computed as the average of F at-age for ages 1 to 3. An F-at-age is calculated for each combination (year, quarter, area), taking into account the selectivity-at-length and the growth model applied to the population ages in the corresponding quarter. An annual summary of F-at-age is calculated by averaging the quarterly F-at-age values. Internally, the model calculates total annual catches stepping through the four quarters and applying the relevant F in each quarter; the resulting catches by quarter are then summed to get the annual catch.

Recruitment estimated from the assessment:

- The assessment model starts at age 0 and, hence, recruitment in the model refers to abundance of age 0 shrimp in the population. Age 0 shrimp are almost totally absent from the survey or the commercial catches, so the first data information about a particular year class comes from the survey and catches of age 1 shrimp in the following year. Between age 0 and age 1 essentially only natural mortality occurs (F is almost identical to 0 at age 0).

Table 1. Settings of the final SS3 assessment model (as of WKPAND 2022) for northern shrimp (*Pandalus borealis*) in Skagerrak and Norwegian Deep (ICES Division 3.a and 4.a East). The final model refers explicitly to the SS3 model with the median natural mortality at age vector, however, all three scenarios are listed in the table. The table columns detail parameter name, number of estimated parameters, the initial values (from which the numerical optimization is started) and the intervals allowed for the parameters. The values estimated by maximum likelihood (MLE) are not included as they will change each year in the new ensemble approach. Parameters in bold are set and not estimated by the model.

PARAMETER NAME	NUMBER ESTIMATED	INITIAL VALUE	BOUNDS (LOW,HIGH)
Natural mortality			
M (age classes 0.5, 1.5, 3.5, 7.5)	-	**Median - 1.709, 1.019, 0.699, 0.577** **Lower – 1.356, 0.809, 0.554, 0.458** **Higher – 1.964, 1.171, 0.803, 0.664**	-
Stock and recruitment			
Ln(R0)	1	17.96	(3,30)
Steepness (h)	1	0.69	(0.1,1)
Recruitment variability (σR)	1	0.53	(0,2)
Ln (Main recruitment deviation): 1984–current year	39 (+1 each year)	-	-
Ln (Early recruitment deviation): 1978-1983	6	-	-
Recruitment autocorrelation	1	0.26	(0,1)
Recruitment distribution			
RecrDist in area 1 (Jan)	-	**0**	-
RecrDist in area 2 (Jan)	1	0.23	(-35,25)
RecrDist in area 2 (Jan) SE	-	**1.5**	-
RecrDist in area 2 (Jan) auto-corr	-	**0**	-
Growth (both sexes)			
K (young)	1	0.47	(0.2,0.8)
L at minimum age	1	0.7	(0–4)
L at max age	1	2.67	(2,4)
CV of young individuals	1	0.12	(0.005–0.40)
CV of old individuals	1	0.05	(0.005–0.40)
Length-weight (both sexes)			
A	-	**0.0016**	-
B	-	**2.7532**	-
Maturity at length (for females)			
Length (cm) at 50% mature	-	**1.97**	-
Slope	-	**-10.3**	-
Eggs per kg (intercept)	-	**1**	-
Eggs per kg (slope)	-	**0**	-
Hermaphroditism			
Age at inflection (sex change)	1	1.08	(0,8)
SD (sex change)	1	2.33	(0.1,21.3)
Asymptote (sex change)	-	**1**	-

Parameter name	Number estimated	Initial value	Bounds (low,high)
Fraction female			
Fraction of population female	-	**1e-06**	-
Initial catches			
Initial catches	-	**Average of 1965-1969**	-
Initial fishing mortality			
Initial F fleet 1 (DK3a) season 1	1	0.04	(0,8)
Initial F fleet 3 (NOR3a) season 1	1	0.07	(0,8)
Initial F fleet 4 (NOR4a) season 1	1	0.08	(0,8)
Initial F fleet 5 (SWE3a) season 1	1	0.12	(0,8)
Initial F fleet 1 (DK3a) season 2	1	0.06	(0,8)
Initial F fleet 3 (NOR3a) season 2	1	0.07	(0,8)
Initial F fleet 4 (NOR4a) season 2	1	0.08	(0,8)
Initial F fleet 5 (SWE3a) season 2	1	0.16	(0,8)
Initial F fleet 1 (DK3a) season 3	1	0.07	(0,8)
Initial F fleet 3 (NOR3a) season 3	1	0.05	(0,8)
Initial F fleet 4 (NOR4a) season 3	1	0.04	(0,8)
Initial F fleet 5 (SWE3a) season 3	1	0.14	(0,8)
Initial F fleet 1 (DK3a) season 4	1	0.04	(0,8)
Initial F fleet 3 (NOR3a) season 4	1	0.04	(0,8)
Initial F fleet 4 (NOR4a) season 4	1	0.02	(0,8)
Initial F fleet 5 (SWE3a) season 4	1	0.09	(0,8)
Selectivity (logistic)			
Commercial trawl fleets			
Size at inflection fleet 1 (DK3a)	1	1.6	(0.35,3.45)
Size 95% width fleet 1 (DK3a)	1	0.3	(0.1,3.45)
Retained length at inflection fleet 1 (DK3a)	1	1.1	(0.2,30)
Retained length width fleet 1 (DK3a)	1	0.2	(-5,30)
Size at inflection fleet 2 (DK4a)	1	1.5	(0.35,3.45)
Size 95% width fleet 2 (DK4a)	1	0.3	(0.1,4.5)
Retained length at inflection fleet 2 (DK4a)	1	1.2	(0.2,30)
Retained length width fleet 2 (DK4a)	1	0.2	(-5,30)
Size at inflection fleet 3 (NOR3a)	1	1.6	(0.35-3.45)
Size 95% width fleet 3 (NOR3a)	1	0.3	(0.1-4.5)
Retained length at inflection fleet 3 (NOR3a)	1	1.3	(0.2,30)
Retained length width fleet 3 (NOR3a)	1	0.1	(-5.1,30)
Size at inflection fleet 4 (NOR4a)	1	1.6	(0.35,3.45)
Size 95% width fleet 4 (NOR4a)	1	0.4	(0.1,4.5)
Retained length at inflection fleet 4 (NOR4a)	1	0.7	(0.2,30)

Parameter name	Number estimated	Initial value	Bounds (low,high)
Retained length width fleet 4 (NOR4a)	1	0.3	(-5.1,30)
Size at inflection fleet 5 (SWE3a)	1	1.8	(0.35,3.45)
Size 95% width fleet 5 (SWE3a)	1	0.5	(0.1,4.5)
Retained length at inflection fleet 5 (SWE3a)	1	1.7	(0.2,30)
Retained length width fleet 5 (SWE3a)	1	0.1	(-5.1,30)
Size at inflection fleet 6 (SWE4a)	1	1.5	(0.35,3.45)
Size 95% width fleet 6 (SWE4a)	1	0.4	(0.1,4.5)
Retained length at inflection fleet 6 (SWE4a)	1	1.6	(0.2,30)
Retained length width fleet 6 (SWE4a)	1	0.1	(-5.1,30)
Norweigan survey			
Size at inflection NORSURVEY3a (fleet 7)	1	1.6	(0.35,3.45)
Size at 95% width NORSURVEY3a (fleet 7)	1	0.5	(-5,4.5)
Size at inflection NORSURVEY4a (fleet 8)	1	1.6	(0.35,3.45)
Size at 95% width NORSURVEY4a (fleet 8)	1	0.4	(0.1,4.5)
Catchability (NOR survey)			
Survey 3a			
Ln(Q) - catchability	-	**-0.594**	-
Survey 4a			
Ln(Q) - catchability	-	**-0.681**	-

C.2. Model used as basis for advice

The assessment model used as the basis for advice for *Pandalus* in 27.3.a4.a is the Stock Synthesis (Version 3) model fitted in an ensemble approach.

C.3. Assessment model configuration

Type	Description	Year range	Age/length range
Landings	Total landings in tonnes, split by area, quarter, and fleet	1970–last data year	-
Discards	Total discards in tonnes, spilt by area, quarter and fleet	2008–last data year (start date varys by country)	-
Length frequency distributions (LFDs)	Catch (sorted and unsorted) in numbers per length class and sex, spilt by area, quarter and fleet	1990–last data year (start date varys by country)	Length classes range 0.2–3.5 cm
Maturity ogives	Empirical maturity at length estimated from survey data	-	-

Type	Description	Year range	Age/length range
Naturality mortality	Natural mortality at age assumed to be costant for the entire time series	-	0–8+
Survey indices	Biomass index from survey by area	1984–last data year	2–8+
Survey LFDs	Catch in numbers per length class and sex, spilt by area and quarter	1984–last data year	Length classes range 0.2–3.5 cm
SSB index	SSB proportional to fecundity	1988–last data year	0–8+

D. Short-term prediction

Model used: Probabilistic projection based on assessment model dynamics.

Software used: SS3 and ensemble approach described in ICES (2022).

Initial stock size: As estimated from the stock assessment; Recruitment at-age 0 is derived from stock-recruitment function with autocorrelation on recruitment.

Maturity: Maturity-at-length as in assessment.

Weight-at-length in the stock: Weight-at-length as in assessment is used.

Exploitation pattern: Selection-at-length as in assessment.

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

E. Medium-term prediction

Not conducted on a regular basis for this stock.

F. Long-term prediction

Not conducted on a regular basis for this stock.

G. Biological reference points

	Type	Value	Technical basis
MSY Approach	MSY $B_{trigger}$	0.8 x $B_{30\%}$	Relative value. Set at 80% of B_0 x 30% (B_{MSY}). 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.
	F_{MSY}	$F_{B30\%}$	Relative value. Set as the F which will achieve B_0 x 30% (B_{MSY}). 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.
Precautionary	Blim	0.15 x B_0	Relative value. Set at 15% of B_0, which is approximately the average B_{loss} for the three models in the ensemble.

Approach	B_{pa}=MSY $B_{trigger}$	0.8 x $B_{30\%}$	Relative value. Set at 80% of B_0 x 30% (B_{MSY}). 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.
	Fpa	1.13 x F_{MSY}	$F_{p0.5}$. Relative value. The F that leads to SSB ≥ B_{lim} with 95% probability.

H. Other issues

H.1. Biology of species

H.2. Current fisheries

H.3. Management and advice

H.4. Others (e.g. age terminology)

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