16.4.3.1. ICES fisheries management reference points for category 1 and 2 stocks

Summary

This document provides a description of the reference points used by ICES, including the definition of the reference values, their general basis and suggested approaches for their calculation.

ICES refers to two types of reference points when providing fisheries advice for category 1 stocks: precautionary approach (PA) reference points and maximum sustainable yield (MSY) reference points. The PA reference points are used when assessing the state of stocks and their exploitation relative to the precautionary approach objectives. The MSY reference points used in the advice rule applied by ICES are aimed at producing advice consistent with the objective of achieving MSY. Table 16.4.3.1.1 lists the purpose and basis of each reference point. All biomass reference points are in units of spawning-stock biomass (SSB), unless otherwise indicated.

The PA reference points and the methods for estimating values were discussed in a series of precautionary approach and reference point workshops between 2001 and 2003. This process led to the report of the Study Group on Precautionary Reference Points for Advice on Fishery Management in 2003 (ICES, 2003). Annex 1 of that report provided guidance for reference point estimation. Most of the process and guidance described in ICES 2003 are still relevant and forms, with minor modifications, the present basis for ICES precautionary approach.

The guidance for estimation of MSY reference points was developed based on the findings of four workshops: WKMSYREF2 (ICES, 2014), WKMSYREF3 (ICES, 2015), WKMSYREF4 (ICES, 2016), WKGMSE3 (ICES, 2020a) Rindorf *et al.* (2017).

Table 16.4.3.1.1 The definition and basis of precautionary approach (PA) and MSY reference points used by ICES to assess the state of stocks and exploitation, and to provide advice on fishing opportunities.

PA reference point	Definition	Basis
B_{lim}	A deterministic biomass limit below which a stock is considered to have reduced reproductive capacity.	The biomass below which recruitment reduces with spawning-stock biomass (SSB), e.g. the change point of a segmented regression. See further guidance below.
F_{lim}	Exploitation rate which leads SSB to B_{lim}.	The fishing mortality rate (F) that in stochastic equilibrium will result in median (SSB) = B_{lim} (i.e. 50% probability of SSB being above or below B_{lim}).
B_{pa}	A stock status reference point above which the stock is considered to have full reproductive capacity, having accounted for estimation uncertainty.	The value of the estimated SSB, which ensures that the true SSB has less than 5% probability of being below B_{lim}, i.e. the 95th percentile of the distribution of the estimated SSB if the true SSB equals B_{lim}. $B_{pa} = B_{lim} \times \exp(1.645 \times \sigma)$, where σ is the standard deviation of ln(SSB) at the start of the year following the terminal year of the assessment. If σ is unknown, 1.4 can be used as a default for "$\exp(1.645 \times \sigma)$", equivalent to $\sigma = 0.20$.
F_{pa}	An exploitation rate reference point below which exploitation is considered to be sustainable, having accounted for estimation uncertainty.	The fishing mortality including the advice rule that, if applied as a target in the ICES MSY advice rule (AR) would lead to SSB ≥ B_{lim} with a 95% probability (also known as Fp05). The derivation of F_{pa} should include the expected stochastic variability in biology and fishery, as well as advice error.
$B_{escapement}$	For short-lived species, a deterministic biomass limit below which a stock is considered to have reduced reproductive capacity, including any identified additional biomass need.	B_{lim}, plus an additional biomass, if the advice is based on a deterministic forecast.

Table 16.4.3.1.2 The purpose and basis of maximum sustainable yield (MSY) reference points used by ICES to assess the state of stocks and exploitation, and to provide advice on fishing opportunities.

MSY reference point	Purpose	Basis
F_{MSY}	The F expected to give maximum sustainable yield in the long term.	F that provides maximum yield, given the current assessment/advice error, and biology and fishery parameters, constrained so that the long-term probability of SSB < B_{lim} is ≤ 5% when applying the ICES MSY advice rule (AR): $F = F_{MSY}$ (if SSB ≥ MSY $B_{trigger}$), $F = F_{MSY} \times$ SSB/MSY $B_{trigger}$ (if SSB < MSY $B_{trigger}$).
MSY $B_{trigger}$	A lower bound of the expected range of SSB when the stock is fished at F_{MSY}. The point at which F is reduced when applying the ICES MSY advice rule (AR).	MSY $B_{trigger}$ = maximum (B_{pa}, the 5th percentile of the distribution of SSB when fishing at F_{MSY}), modified according to the scheme for determining MSY $B_{trigger}$ (described in the section on MSY reference points).

PA reference points – Guidelines for estimation of PA reference points for category 1 stocks

B_{lim} is the key PA reference point. The other precautionary approach points (B_{pa}, F_{lim}, and F_{pa}) are all estimated from B_{lim}. In a few cases, the available information does not allow direct estimation of B_{lim}; B_{pa} is then estimated directly, and B_{lim} may be derived from B_{pa}.

For most stocks, all the PA reference points can be established and used directly. However, for short-lived species, there are some extra considerations and differences, as explained under step 4 below. In this context, short-lived species are species characterized by high natural mortality and year classes contributing significantly to the fishery for only one or a maximum of two years.

The framework for PA reference point estimation for category 1 stocks includes the following steps:

1. Identifying appropriate data.
2. Identifying stock type.
3. Estimating biomass limit reference points.
4. Deriving PA reference points from limit reference points.

Reference points can be estimated using the standard ICES software (EqSIM) or from a self-consistent MSE simulation model when one is conducted (ICES, 2020a, 2020b).

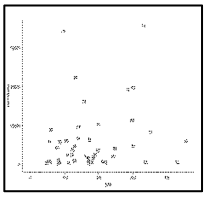
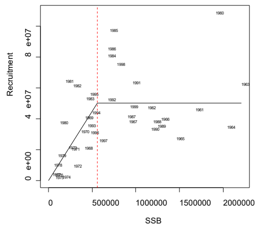
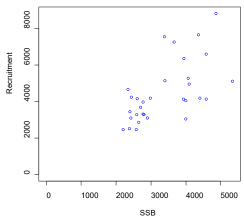
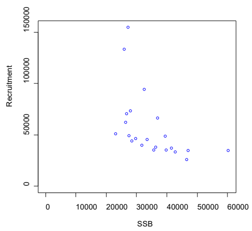
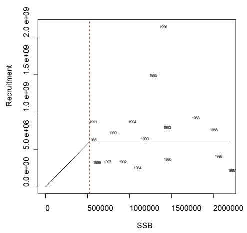
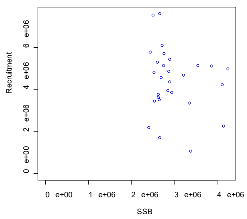
Step 1. Identifying appropriate data

The estimation of reference points is based on assessment data and stock–recruitment (S–R) plots using the most recent data (i.e. S–R outputs from the most recent assessment). The full time-series of the stock and recruitment should be used, unless very strong evidence exists to do otherwise (e.g. a change in regime or productivity). Any S–R pairs which are considered poorly estimated should not be included in the estimation. If quantitative criteria are not available to evaluate the estimation of a specific S–R pair, the evaluation can be based on expert judgment.

Step 2. (Stock type identification) and 3. (Estimation of biomass limit reference point)

ICES stocks with analytical assessments and a time-series of paired S–R values can be grouped by type. A summary of stock types and the appropriate reference point estimation methods is given in Table 16.4.3.1.3.

Table 16.4.3.1.3 Summary of stock types and reference point estimation.

Stock characteristics			Limit point estimation options dependent on data and specific stock information	
Stock type	S–R plot characteristics	Sample S–R plot	B_{lim} estimation possible according to standard method	B_{lim} estimation possible on the basis of stock-specific method or judgement
Type 1	Spasmodic stocks – stocks with occasional large year classes.		B_{lim} is based on the lowest SSB, where large recruitment is observed – unless F has been low throughout the observed history, in which case B_{loss} = B_{pa}.	
Type 2	Stocks with a wide dynamic range of SSB, and evidence that recruitment is or has been impaired.		B_{lim} = segmented regression change point.	
Type 3	Stocks with a wide dynamic range of SSB, and evidence that recruitment is or has been impaired, with no clear asymptote in recruitment at high SSB.			B_{lim} may be close to the highest SSB observed. The estimate depends on an evaluation of the historical fishing mortality.
Type 4	Stocks with a wide dynamic range of SSB, and evidence that recruitment increases as SSB decreases.			No B_{lim} from this data, only the PA reference point. (B_{loss} would be a candidate for B_{pa}).
Type 5	Stocks showing no evidence of impaired recruitment or with no clear relation between stock and recruitment (no apparent S–R signal).		B_{lim} = B_{loss}	
Type 6	Stocks with a narrow dynamic range of SSB and showing no evidence of past or present impaired recruitment.			No B_{lim} from this data, only the PA reference point (B_{loss} could be a candidate for B_{pa}, however, this is dependent on considerations involving historical fishing mortality).

Type 1: Stocks with occasional very strong year classes (spasmodic stocks)

The stocks in this group have unique biological characteristics which justify a specific approach. They exhibit some points well above the cloud of points in a stock–recruitment scatter plot. However, the time-series are usually too short to establish the frequency of such rare events with any accuracy. Examples of such stocks are: most haddock stocks, Norwegian spring-spawning herring, and Western horse mackerel. Establishing biomass reference points for such stocks is often difficult due to the population dynamic depending on the occurrence of strong year classes. Two subcases are considered:

A) *Stocks for which an extensive range of SSB has been estimated, where the lowest SSB that has previously given high recruitment can beused as B_{lim} (e.g. haddock in the North Sea, West of Scotland, and Skagerrak). Here, the analysis should focus on establishing the minimum SSB above which strong year classes have been observed; this SSB would constitute a possible B_{lim} candidate. Using this B_{lim} to determine the corresponding B_{pa}, F_{lim}, and F_{pa}, these reference points should be based on S–R pairs from periods where the very strong year class had little or no influence on the SSB, i.e. use the period before the year that produced the strong year class and the period after which the strong year class contributed only little to the SSB.*

B) *Stocks where F has been low and the full range of SSB may not have been explored (e.g. Western horse mackerel). Approaches for such cases are outlined under type 6.*

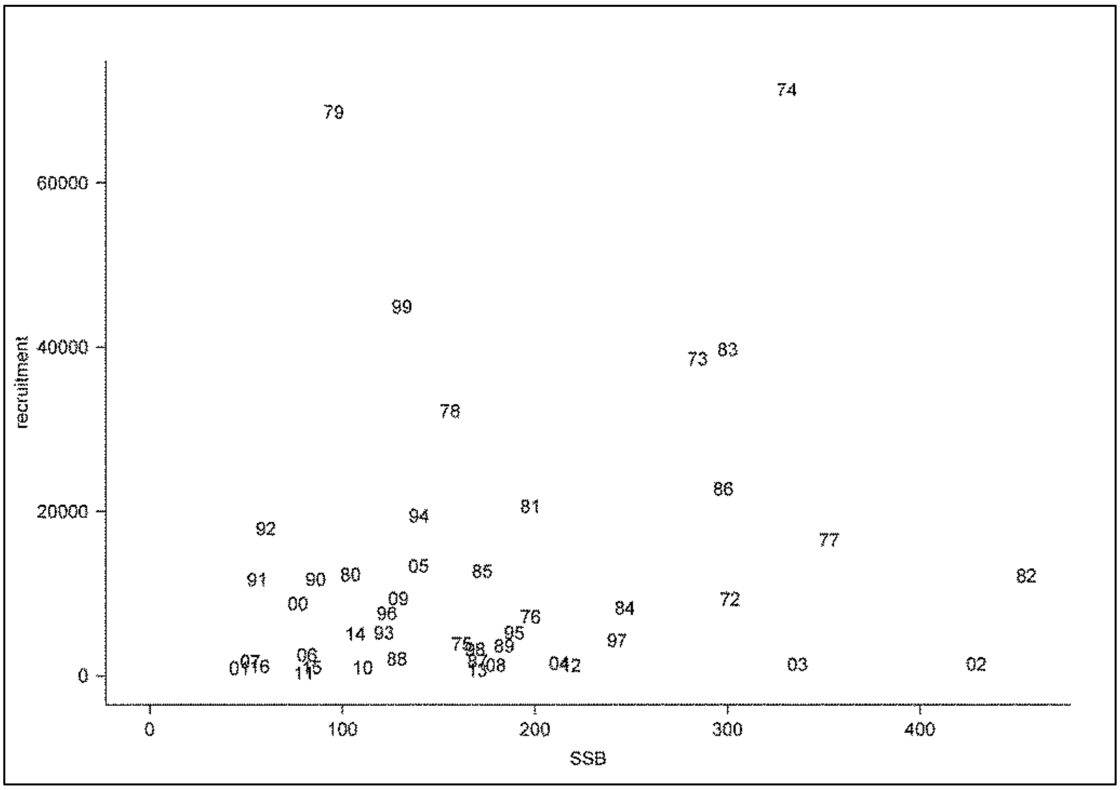


Figure 16.4.3.1.1 Stock type 1, showing an example with an extensive range of estimated SSB. A candidate B_{lim} here would be around 100 kt – the SSB that gave rise to the large 1979-year class.

Type 2: Stocks with a wide dynamic range of SSB and evidence that recruitment is or has been impaired

For stocks with a distinct change point in the S–R relationship, the scatterplot can be divided into a slope and a plateau region. A change point in the S–R relationship can be estimated and the SSB that corresponds to the estimated point is defined as B_{lim}. For these stocks, if a stable change point in a segmented regression can be estimated, then this would be a good candidate for B_{lim}. If the performance of the segmented regression analysis is found to be unsatisfactory (e.g. an unrealistically high change point), or if there are specific reasons for a modified approach, alternative approaches for estimating B_{lim} should be investigated in particular exploring the use of alternative S-R functions.

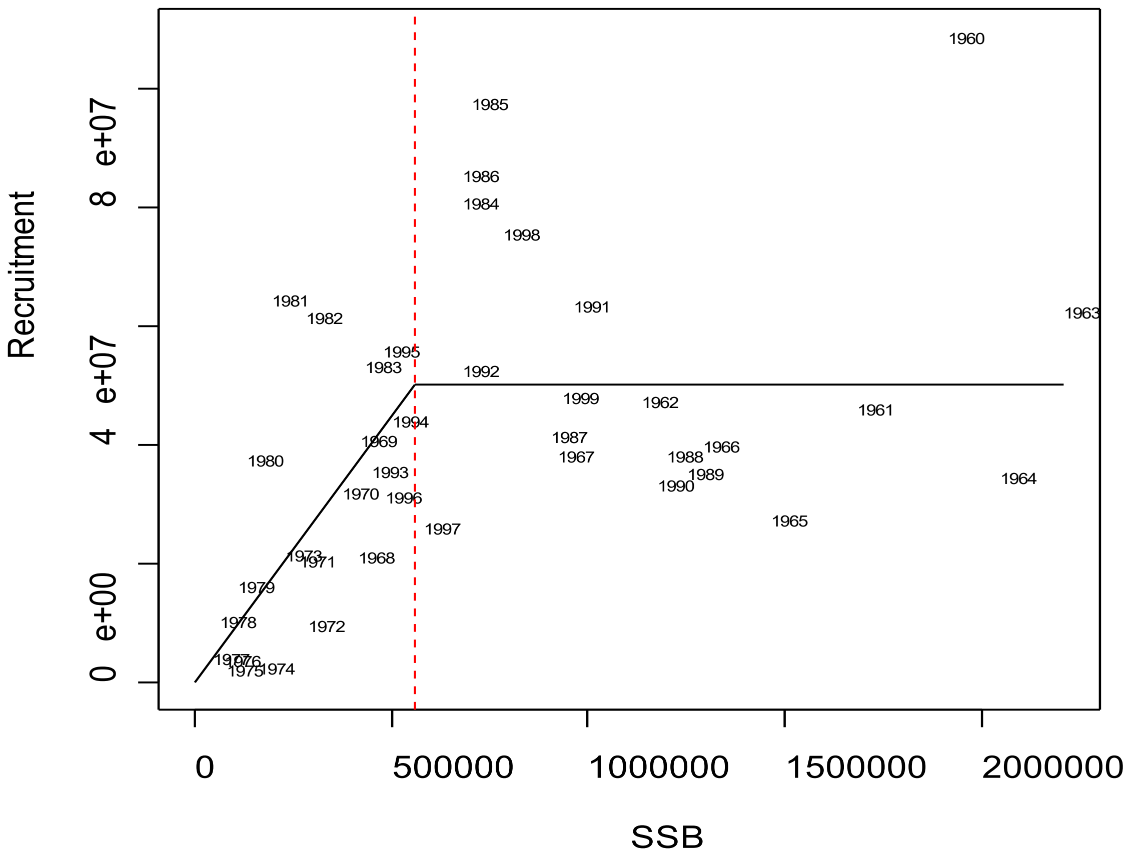


Figure 16.4.3.1.2 Stock type 2, showing an example with a well-defined change point.

Type 3: Stocks with a wide dynamic range of SSB and evidence that recruitment is or has been impaired, with no clear asymptote in recruitment at high SSB

No distinct plateau in the S–R relationship is present in these stocks; however, stock recruitment appears to reduce along with SSB for the range of historical observations. First, the likelihood of high fishing mortality before the start of the time-series should be considered, and whether the pattern in the observed recruitment reflects a period of impaired recruitment, in which case B_{lim} may be higher than the observed SSBs. In such cases, it may be suspected that fishing mortality has been high before the historical time-series started, and that all historical data are within the range of impaired recruitment. B_{lim} may be at higher SSB values than observed. This decision should be based on evaluations of other data, especially the historical data on fishing mortality.

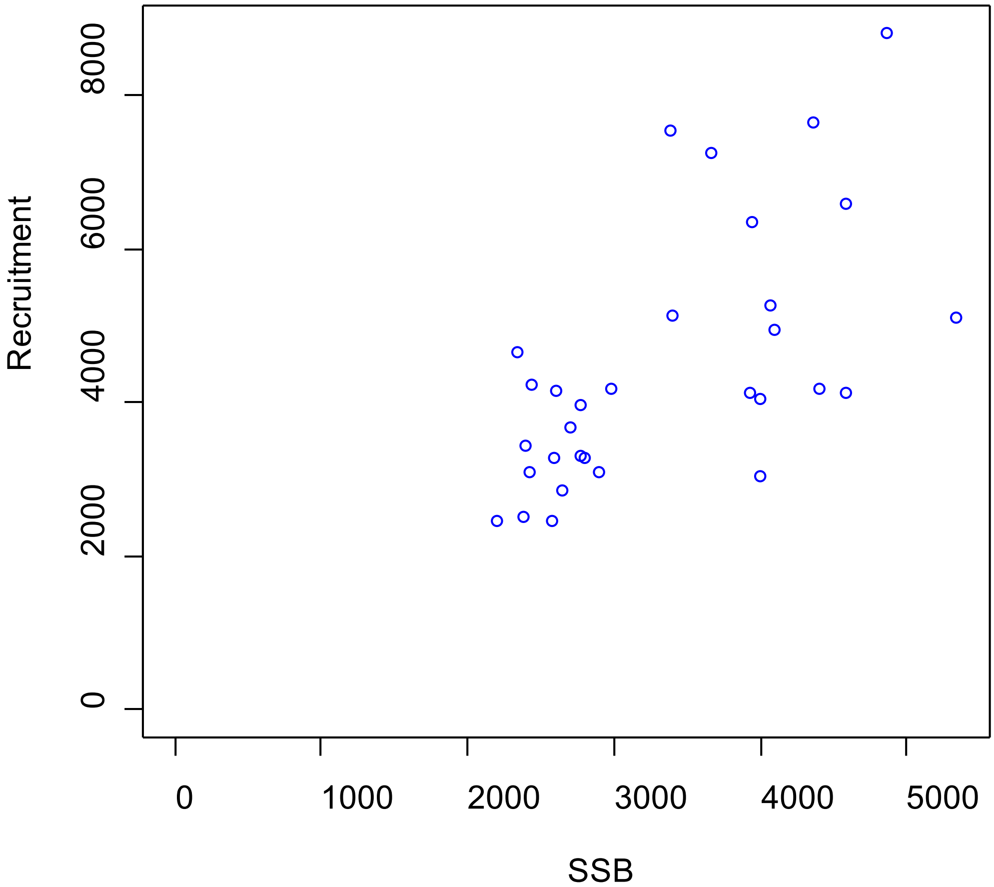


Figure 16.4.3.1.3 Stock type 3, showing an example with no distinct plateau in recruitment.

Type 4: Stocks with a wide dynamic range of SSB and evidence that recruitment increases as SSB decreases

Stocks where R increases as SSB decreases. For this inverse S–R relationship, it is not possible to estimate limit reference points based on historical information. B_{loss} may be used as a candidate value for B_{pa}. B_{loss} should be taken from a stable part of the assessment and should not be from recent years if SSB is declining, since this could lead to a declining B_{lim} as the stock declines.

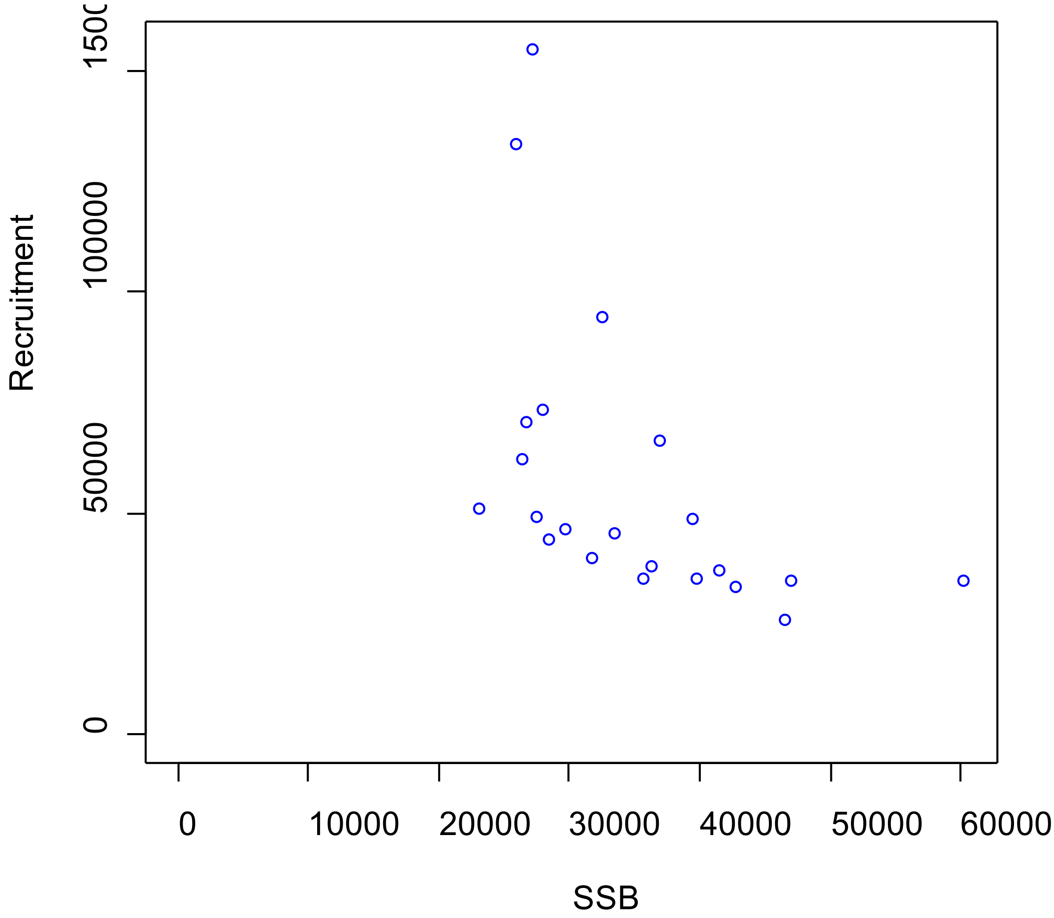


Figure 16.4.3.1.4 Stock type 4, showing an example with recruitment increasing as SSB decreases.

Type 5: Stocks with no evidence that recruitment has been impaired or with no clear relation between stock and recruitment (no apparent S–R relationship)

Stocks with a clear plateau in the S–R relationship, where a wide range of F and SSB has been observed; however, no evidence exists that recruitment has been impaired. For these stocks, B_{loss} is identified as a candidate value of B_{lim}, below which the dynamics of the stock are unknown. B_{loss} should be taken from a stable part of the assessment and should not be from recent years if SSB is declining, since this could lead to a declining B_{lim} as the stock declines.

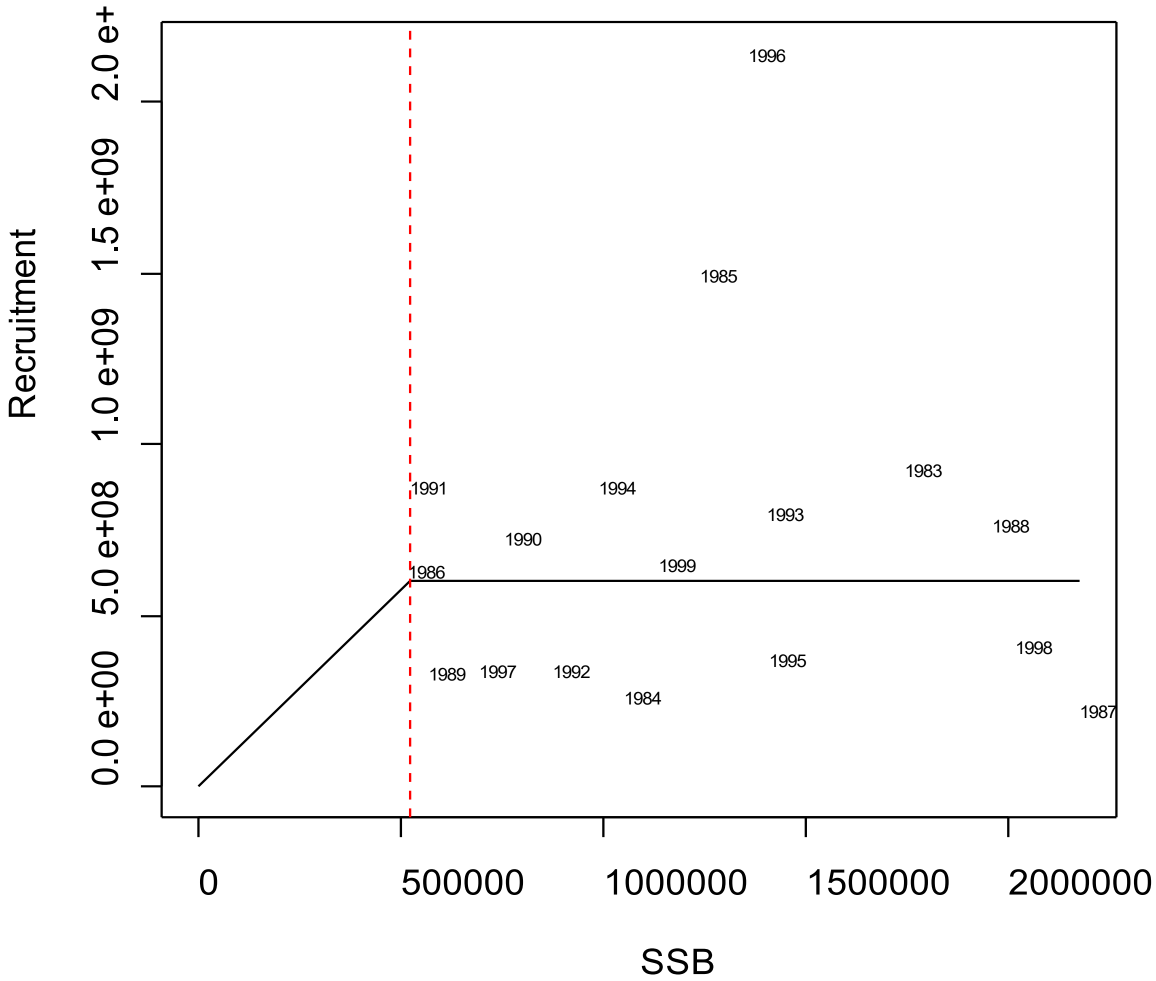


Figure 16.4.3.1.5 Stock type 5, showing an example with no evidence that recruitment has been impaired.

Type 6: Stocks with a narrow dynamic range of SSB, and no evidence that recruitment is or has been impaired

Some stocks have a small dynamic range in SSB, which makes it difficult to determine the S–R relationship and therefore, the biomass reference points. The reason for this is that there is only one SSB ”level” to determine the S–R curve. ICES deals with these cases individually.

If the stock is exploited at a high fishing mortality, above what seems reasonable based on other reference points (e.g. yield per-recruit reference points) or from experience with similar stocks, and if this has been the prevailing situation for most or all of the time-series for the available data, then the stock should be considered as depleted and the estimated SSB as representing a stock that may not reproduce to its fullest potential. In this case, a reasonable B_{pa} will need to be defined based on the historical level of F. This B_{pa} is likely to be above the SSB observed for this stock if F has been above any possible candidate of F_{pa}.

If, on the other hand, the fishing mortality has been low, judged by conventional reference points and experience with similar stocks, then this may be a stable stock for which the B_{pa} should be defined as the B_{loss} value. B_{loss} should be taken from a stable part of the assessment and should not be from recent years if SSB is declining, since this could lead to a declining B_{lim} as the stock declines.

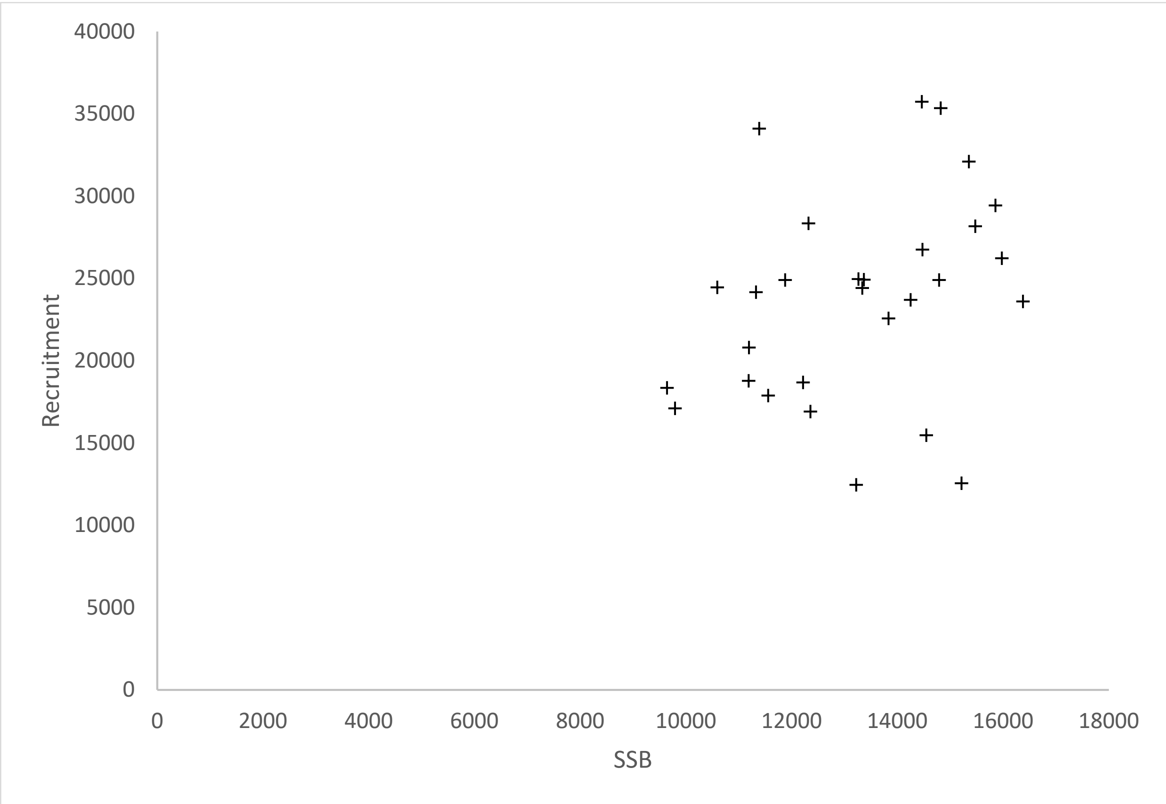


Figure 16.4.3.1.6 Stock type 6, showing an example with a narrow range of SSB and stable recruitment.

Step 4. Deriving other PA reference points from B_{lim}

Estimating B_{lim} from B_{pa}

For practical purposes, in cases where B_{pa} can be estimated but B_{lim} cannot, a proxy for B_{lim} is considered based on the inverse of the standard factor for calculating B_{pa} from B_{lim} (i.e. a B_{lim} proxy equal to $B_{pa}/1.4$). It should be noted that when calculating the B_{lim} proxy the factor 1.4 (equivalent to σ = 0.20) should be applied, instead of exp(1.645 × σ) with σ from the assessment uncertainty in SSB in the terminal year.

B_{pa}

$B_{pa} = B_{lim} \times \exp(1.645 \times \sigma)$, with σ estimated from the assessment uncertainty in SSB in the terminal year (σ is the estimated standard deviation of ln(SSB) in the final assessment year). If σ is unknown, 1.4 can be used as a default for "exp(1.645 × σ)", equivalent to σ = 0.20.

F_{lim}

F_{lim} is derived from B_{lim} in one of the following ways:

a) The preferred method is simulating a stock with a segmented regression S–R relationship, with the point of inflection at B_{lim}, thus determining the $F = F_{lim}$ which, at equilibrium, yields a 50% probability of SSB > B_{lim}. Note that this simulation should be conducted based on a fixed F (i.e. without inclusion of a $B_{trigger}$) and without inclusion of assessment/advice errors (In the MSY R package (also known as EqSim), this means $B_{trigger}$, F_{cv}, and F_{phi} should all be set to zero).

b) In the alternative method, R/SSB is calculated at B_{lim}, followed by the calculation of the slope of the replacement line at B_{lim}. Inverting this leads to SSB/R, which can be used to derive F_{lim} from the curve of SSB/R against F. An example is shown in Figure 16.4.3.1.7.

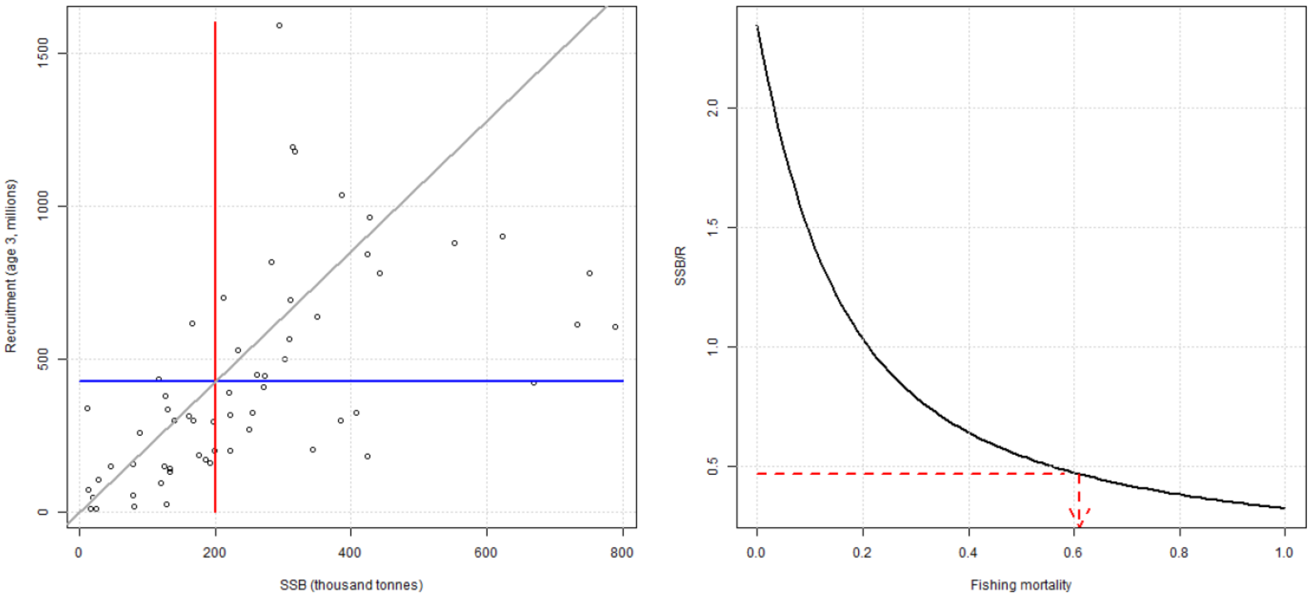


Figure 16.4.3.1.7 Left: Stock–recruitment relationship with a wide dynamic range of SSB and evidence that recruitment has been impaired. The red line represents B_{lim} (here, 200 kt), the blue line is the mean R at B_{lim}, and the gray line is the replacement line with the slope of *x*. Right: SSB/R against mean F, where the red-dotted line is at 1/slope and determines F_{lim} (here, 0.61).

R package: icesAdvice

The ICES Secretariat has released an R package on CRAN, called icesAdvice. It provides two simple functions, called Bpa() and Fpa(), that can be used to calculate those reference points.

R package: msy

The msy R package (EqSim) is a collection of methods to estimate equilibrium reference points for fish stocks: https://github.com/ices-tools-prod/msy.

Short-lived species

Short-lived species are species with a lifespan restricted to 4–6 years. These stocks exhibit a high level of natural mortality (mean natural mortality around 1.0 or even greater). The yearly variation in natural mortality can be large due to predation and the influence of environmental conditions, highly variable recruitment, and a low age-at-first capture. Fishing mortality is generally lower than natural mortality. The size of SSB for a short-lived fish species is very sensitive to recruitment due to the few age groups in the natural population. Management should ensure a sufficient spawning-stock size as the future of the stock is highly dependent on annual recruitment.

For stocks of short-lived species, the evaluation of B_{lim} is carried out in the same manner as for stocks of long-lived species. B_{pa} is estimated from B_{lim}, using the same methods as for long-lived stocks, but with a default $\sigma = 0.3$, if the terminal year SSB uncertainty is not available from the assessment.

ICES does not utilize F reference points to determine exploitation status of short-lived species.

MSY reference points – Guidelines for estimation of F_{MSY} and MSY $B_{trigger}$ for category 1 stocks

Definition of yield

In selecting F_{MSY}, it is necessary to define yield (Y) from the fishery. In ICES advice, the yield is defined as either landings or catch. For some fisheries, discarding is known to be negligible and landings and catches may be considered equal. However, if catches have a significant below-minimum catch/conservation size, or a significant discarded component (including slippage or high-grading), there are two important considerations for the selection of an appropriate F_{MSY}. Firstly, in the definition of what constitutes the yield in the context of MSY, and secondly, in the calculation of F to produce the maximum yield. In this respect, F should always be the total F for catch, as used by ICES to provide advice. However, in the event that only landings data are available, the F used only reflects the landings. The appropriate definition of yield to use is a choice for policy, and, following discussions with clients, ICES defines yield as the catch above the minimum catch/conservation size. When the selection pattern corresponding to this cannot be estimated, ICES uses the recent wanted catches (catches above MCRS) selection to define yield.

Estimating yield (MSY) in the simulations

The mean of the simulated long-term yield can have undesirable properties when yield distributions are highly skewed (with a high proportion of values in the tails of the distribution) and may occasionally contain very large values. The median of the distribution at each F is often considered to be more robust to these issues. In cases where the distribution of yields is unimodal and with short tails in the distribution, the two values are generally similar. Therefore, it is recommended that the median yield curve versus F is the basis for the estimation of F_{MSY} (as the value of F that maximizes yield).

Input data

The parameters describing properties of the population biology and the fishery, such as weight-at-age in stock and catch, maturity, natural mortality, and fishery selection pattern, should be derived from the last ten years of available data by default. When clearly documented persistent trends exist in one or more of the above parameters, the period can be decreased to three or five years. Conversely, the period can be extended to include more years if there is no evidence of temporal trends. If data on variability of e.g. maturity is not included in the assessment, but is available from other sources, it should also be introduced, even if this variability has not been incorporated in the stock assessment (whilst ensuring the mean is not changed). When introducing data from multiple separate analyses, care must be taken to ensure that multiple sources of variability are dealt with correctly, and additional sources of variation take account of the presence of other changes in the simulations.

Implementation of stochasticity

There are several descriptions of how to implement stochasticity, process and estimation uncertainty, and correlated errors (Kell *et al.,* 2005; ICES, 2013; Punt *et al.,* 2016). Variability in biological parameters such as growth, maturation, and natural mortality can be included, using either a bootstrap resampling approach or parametric simulation. As a minimum, realistic (estimated) uncertainties should be used when predicting recruitment from an S–R relationship, as this is usually the main source of variability. Inclusion of stochastic draws from interannual variability in recruitment is required for precautionary considerations. This can be either parametric simulation or a bootstrap resampling of residuals. However, it must include a functional form of the S–R relationship, as discussed in the S–R section below.

In the estimation of the probability of obtaining a stock size below B_{lim}, it is necessary to include realistic estimates of the assessment and advice uncertainty (i.e. including the uncertainty in the short-term forecast). It is preferable that this uncertainty can be estimated from a comparison of forecast F and resulting F taken from the most recent assessment. They may also be estimated within an MSE framework which arguably characterises these uncertainties more accurately (see ICES, 2020a, 2020b). Such stochastic issues may be ignored when the MSY reference points are shown to be at levels relative to PA reference points, where the stochastic issues have no bearing on precautionary considerations. The msy R package used in WKMSYREF3 and WKMSYREF4 varied in the underlying assumptions, e.g. the different constraints that were applied to S–R model parameters (ICES, 2015, 2016). It is important that such underlying assumptions are clearly specified.

Stocks of medium- and long-lived species

The details of the current approach to estimate F_{MSY} are compiled from the reports of WKMSYREF2, WKMSYREF3, WKMSYREF4, WKGMSE3 (ICES, 2014, 2015, 2016, 2020). Considerations provided here relate to medium- and long-lived species. While F_{MSY} is generally considered a property of the stock and fishery, the advice rule (AR), used by ICES to provide advice according to the MSY approach, needs to be precautionary and should conform to the overriding criterion of a greater than 95% annual probability that SSB remains at or above B_{lim} in long-term equilibrium. To determine the F_{MSY} and MSY $B_{trigger}$ values that can be used to produce catch advice under the ICES MSY approach, a procedure that includes assessment and advice error (i.e. uncertainty in the assessment and short-term forecast) is laid out below.

A precautionary F criterion, F_{pa}, established by stochastic simulation, is used by ICES to facilitate the evaluation. The simulations include biological (i.e. recruitment, M, maturity, and growth) and fishery (e.g. selectivity) variability and advice error. The evaluations are carried out using both F_{MSY} and MSY $B_{trigger}$, and are valid for the specific parameters tested.

General four-step procedure to calculate F_{MSY} and MSY $B_{trigger}$

1. F_{MSY} should initially be calculated based on an evaluation with the inclusion of stochasticity in a population (i.e. recruitment, M, maturity, growth) and fishery (e.g. selectivity) as well as assessment/advice error. This is a constant F, which should provide maximum yield without biomass constraints (without MSY $B_{trigger}$). Error is included as this is the condition analogous to management strategy evaluations (MSEs) that will prevail in practice. Note that in order to ensure consistency between the precautionary and the MSY frameworks, F_{MSY} is not allowed to be above F_{pa}; therefore, if the F_{MSY} value calculated initially is above F_{pa}, F_{MSY} is reduced to F_{pa}.
2. MSY $B_{trigger}$ should be selected to safeguard against an undesirable or unexpected low SSB when fishing at F_{MSY}, following the process described below.
3. The ICES MSY AR should be evaluated to check that the F_{MSY} and MSY $B_{trigger}$ combination fulfils the precautionary criterion of having less than 5% annual probability of SSB < B_{lim} in the long term. The evaluation must include realistic assessment/advice error and stochasticity in population biology and fishery selectivity.
4. If the precautionary criterion evaluated in point 3 is not met, then F_{MSY} should be reduced from the value calculated above until the precautionary criterion is met (i.e. reduce F_{MSY} to $F_{MSY} = F_{pa}$).

The final results of this process (steps 1–4) are the values of F_{MSY} and MSY $B_{trigger}$. ICES provides these values in the advice sheet and uses them to formulate MSY advice and to evaluate the stock status in relation to MSY reference points. The properties of these values are similar to but not the same as F and biomass triggers in an MSE (ICES, 2020a). Step 1 and 2 of this process is discussed in the following sections.

Step 1: F_{MSY}

F_{MSY} should initially be calculated based on an evaluation that includes stochasticity in a population and selectivity, as well as assessment/advice error. This initial F_{MSY} is a constant F, which should provide maximum yield without biomass constraints (without MSY $B_{trigger}$). Error is included as this is the condition analogous to management strategy evaluations (MSEs) that will prevail in practice. Note that in order to ensure consistency between the precautionary and the MSY frameworks, F_{MSY} is not allowed to be above F_{pa}; therefore, if the F_{MSY} value calculated initially is above F_{pa}, F_{MSY} is reduced to F_{pa}.

The following guidance on the selection of S–R relationships for estimating F_{MSY} is mostly extracted from the WKMSYREF3 report (ICES, 2015), where much of this work was carried out, with some additions after the WKMSYREF4 meeting (ICES, 2016).

The stock–recruitment relationship is crucial in the estimation of F_{MSY} and the risk of falling below precautionary biomass reference points. Therefore, substantial effort in the WKMSYREF3 workshop was dedicated to providing guidelines for best practice in the estimation of stock-recruitment relationships. In the workshop, four different S–R relationships were used: Ricker (Ricker, 1954), Beverton-Holt (Beverton and Holt, 1957), segmented regression, and Cadigan (Cadigan, 2013). Others may also be utilized if they are consistent with biological knowledge of the stock. The resulting guidelines are provided in Table 16.4.3.1.4.

Table 16.4.3.1.4 Guidelines for best practice in the selection of stock-recruitment (S–R) relationships used for the estimation of F_{MSY}. Extracted from the WKMSYREF3 report (ICES, 2015), with some additions after the WKMSYREF4 meeting (ICES, 2016). Note that while the use of a segmented regression stock-recruitment function may be required to yield the best estimate of a change point (for setting B_{lim}), other S–R functions may better characterize the whole stock dynamics; thus, use of other relationships is acceptable here. However, care should be taken to ensure that the reference points chosen in accordance with the criteria below do not imply substantively different dynamics at this stage (i.e. the choice should be reasonably consistent with the set B_{lim}).

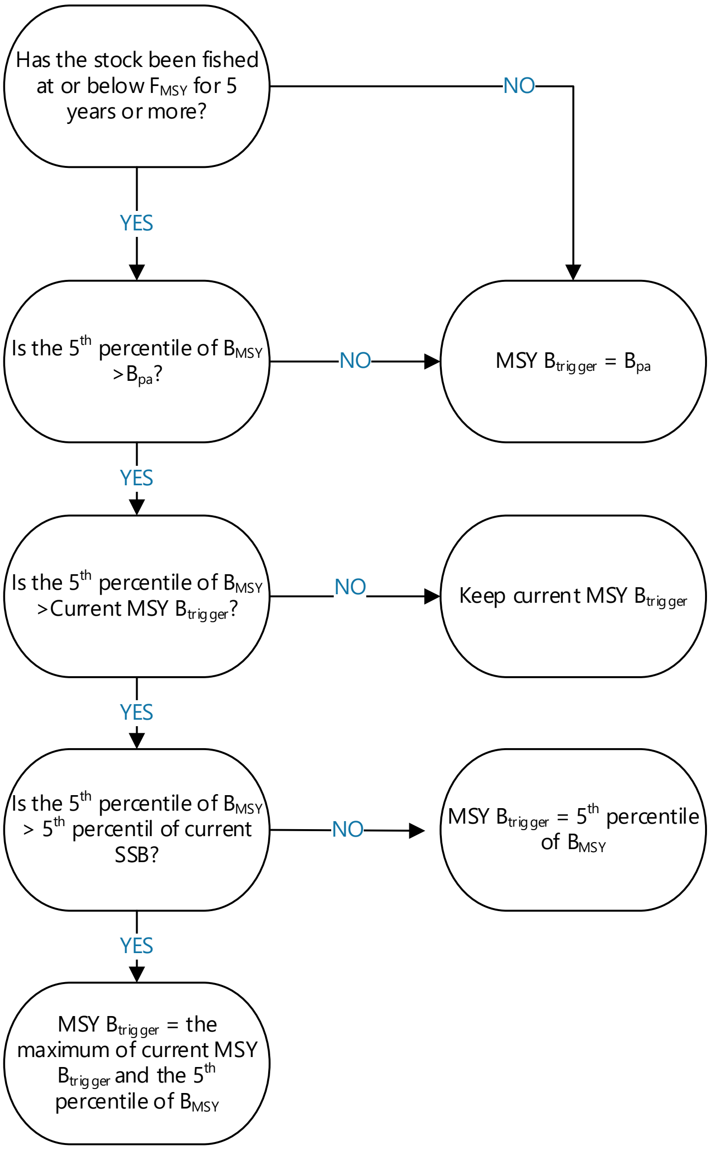
Issues	Recommended action
There is clear evidence that a specific S–R relationship is the correct model.	In this case, the estimation of MSY reference points should be based on the identified S–R relationship, and no other S–R relationships should be included.
It is unclear which S–R relationship provides the best fit to the data, e.g. when several models show similar fits to the data.	Use several, more than one, S–R relationship models having different characteristics and weight the results of the simulations from the various options against each other. Some problems were encountered in the EqSim model with the automatic weighting procedures used to weight the contribution of each relationship, as the weight on one relationship may be substantially higher than on another for no obvious reasons. The methodology uses the distribution of coefficients to weight the different models and may be sensitive to particular formulation of the models, particularly if the model coefficients are correlated (e.g. Beverton-Holt). The comparison of the maximum likelihood models may not necessarily explain why this is happening. In this case, it may be a solution to use a segmented regression.
Individual points are highly influential in the S–R relationship.	Examine the validity of the highly influential data points. If they are considered valid, then keep them in the analysis; the use of a segmented regression or the Cadigan method (Cadigan, 2013) with bootstrap observations may provide a robust option, incorporating the uncertainty associated with the function.
It is suspected that there are prolonged shifts in recruitment success that are unrelated to SSB.	Unless strong evidence exists that a consistent change has occurred, the full time-series of stock and recruitment should be used. Be careful not to mistake periodicity in recruitment success, induced by e.g. cyclic climate conditions, with prolonged shifts. Serial autocorrelation in recruitment (or recruitment deviations from the model) may influence the results and should be included.
Predicted average recruitment at F_{MSY} is substantially higher than the maximum observed.	If average recruitment at F_{MSY} is greater than, e.g. 150% of the maximum observed recruitment, it should be investigated thoroughly. This often results from estimating S–R functions, using monotonically increasing observed S–R values. In this case, a segmented regression can be used (see explanation above).
Stock type (see Table 16.4.3.1.3)	Recommended action
Type 1. Recruitment has occasional very high values.	This type of S–R relationship has so far only been incorporated in the method used for horse mackerel (ICES, 2015). Removing the extreme recruitment values from the analysis for this stock led to suggested F_{MSY} and $F_{P.05}$ values that were lower than when the occasional high recruitments were included. It is recommended, as a minimum, to investigate the sensitivity of the results to the occasional very high recruitments.
Type 2. Stocks with a wide dynamic range of SSB, and showing evidence of recruitment that is or has been impaired.	The default option, if the slope to the origin and plateau can be well established, would be the Beverton-Holt model. The alternative choice of the Ricker model would need to be well justified based on knowledge of the biology of the stock.

Issues	Recommended action
Type 3. Recruitment appears to increase with SSB for all observed values of SSB.	In these cases, F_{MSY} tends to be estimated at very low values as it is assumed in predictions that recruitment is an ever-increasing function of SSB. This seems highly unlikely. To avoid such unrealistic predictions, a segmented regression relationship can be used. The change point of the segmented regression should be at the average of all observed SSBs, under the assumption that the asymptotic SSB does not correspond to impaired recruitment (which requires some expert judgment). However, if F has been low historically, the implication is that the S–R relationship may not follow the observed points. The change point could be placed at B_{loss} and the plateau at mean recruitment.
Type 4. Recruitment appears to decrease with increasing SSB for all observed values of SSB.	This usually results in a Ricker curve or the Cadigan function fitting the points with the descending limb of the function. Hence, maximum recruitment is predicted to occur at unknown SSBs, below the observed minimum. The interpretation that recruitment will increase at SSB values below the lowest observed seems highly risky. To avoid such assumptions and related predictions, a segmented regression relationship can be used. The change point of the segmented regression should be at the lowest observed SSB or, if B_{loss} is used as the value for B_{pa} (see the reference points section above), the change point would be at the B_{lim} proxy.
Type 5 and 6. Constant recruitment is estimated for all values of SSB.	Such relationships should not be included in the estimation. Where constant recruitment appears to be an appropriate model, this should be replaced by segmented regression relationships with the lowest observed SSB as the forced change point.

Step 2: MSY $B_{trigger}$

In the ICES MSY approach, MSY $B_{trigger}$ is defined as the 5th percentile on the distribution of SSB when fishing at F_{MSY}. This calculation does not include assessment/advice error, but includes annual stochasticity in population parameters and fishery selectivity. When a stock declines below MSY $B_{trigger}$, this triggers advice for a reduced fishing mortality compared to F_{MSY}.

For most stocks that lack data on fishing at F_{MSY}, MSY $B_{trigger}$ is set at B_{pa}. However, as a stock starts to be fished consistently with F_{MSY}, it is possible to move towards implementation of a value for MSY $B_{trigger}$ that reflects the 5th percentile definition of MSY $B_{trigger}$. The following scheme, shown as a flowchart, is used to progressively update MSY $B_{trigger}$ from the current value (typically B_{pa}) to the new implementation.



Notes on flowchart notation:

- B_{MSY} denotes the expected equilibrium biomass when fishing at F_{MSY}.
- "Current SSB" denotes the SSB at the start of the year, following the terminal year of the assessment. If the assessment does not have intervals on SSB, a standard deviation of 20%, which is commonly used by ICES and which gives the 5th percentile equal to SSB/1.4, should be used.
- MSY $B_{trigger}$ is expected to be reduced by this process only if the new estimate of the 5th percentile of B_{MSY} is lower than any previous estimate.
- B_{pa}, MSY $B_{trigger}$, and B_{MSY} are in units of SSB.

Stocks of short-lived species

For most stocks of short-lived species, similarly to the long-lived species, the ICES MSY approach is aimed at providing MSY while ensuring that the probability of the stock being below B_{lim} in any single year is no more than 5%. For some stocks, advice is given based on agreed management plans that have been shown to be precautionary. For some other stocks, ICES uses two reference points: MSY $B_{escapement}$ and F_{cap}. Each year, MSY $B_{escapement}$ is estimated to be robust against low SSB and includes a biomass buffer to account for uncertainty in both the assessment and catch advice. In some cases, however, defining an MSY $B_{escapement}$ is not needed; this is because the escapement strategy uses the 95% probability of being above B_{lim} directly.

For many of these stocks of short-lived species, F_{cap} is defined to limit exploitation rates when biomass is high. A large stock is usually estimated with greater uncertainty; when the catch is taken, for example, the uncertainty in the escapement biomass is greater. By capping the F, the escapement biomass is increased in proportion to the stock size, maintaining a high probability of achieving the minimum amount of biomass left to spawn. In some cases (such as following high recruitment), this will result in a median SSB above MSY $B_{escapement}$ in the long term.

The general approach to provide advice based on B_{lim} and a biomass escapement strategy, as explained above, is used by ICES for stocks of short-lived species that either (a) die after spawning, such as capelin, or (b) have such high natural mortality that future SSB is largely independent of survival after spawning, such as North Sea sprat, sandeel or anchovy.

Stocks assessed with biomass dynamics models

The frameworks mentioned so far for PA and MSY reference points depend on appropriate modelling of a stock–recruitment relationship, describing the population and fishery exploitation pattern on the basis of ages (or possibly, lengths). This is not available for stocks assessed with biomass dynamics models, where no age or length structure is considered and a few model parameters (often just one parameter) implicitly capture the combined effects of recruitment, growth, and natural mortality. In these models, the so-called fishing mortality (F) is actually a harvest rate (= catch/stock biomass), which also implies that the stock biomass modelled in these assessments is the exploitable biomass.

For the last few years, it has been common practice in ICES to set reference points based on the deterministic equilibrium relationship between yield, F, and stock biomass. The following table provides a summary.

Reference point	Rationale	Value with a Schaefer model*
F_{MSY}	The F that maximizes the equilibrium curve of yield vs. F	$r/2$
MSY $B_{trigger}$	0.5 B_{MSY}, where B_{MSY} is the biomass corresponding to MSY in the equilibrium curve of yield vs. stock biomass	0.5 B_{MSY} = $0.25\ K$
B_{lim}	Stock biomass corresponding to equilibrium yield equal to half the maximum (i.e. MSY/2)	0.3 B_{MSY} = $0.15\ K$
F_{lim}	The F that drives the stock to B_{lim}, based on the equilibrium curve of stock biomass vs. F	1.7 F_{MSY}
F_{pa}, B_{pa}	Thus far no F_{pa} or B_{pa} reference points have been set for any of these stocks. The stock assessments that have been implemented with these models provide uncertainty intervals around the results; therefore, the probability of F exceeding F_{lim} or the biomass being below B_{lim} in any assessment year can be directly calculated from the assessment.	

* In the Schaefer model, the parameters r and K represent the intrinsic growth rate and equilibrium biomass, respectively, under a no-fishing regime. The reference point values in this column correspond to deterministic equilibrium calculations.

Category 1 stock assessments performed in ICES until now have deployed biomass dynamics models using the standard Schaefer model, with reference points defined by deterministic calculations. However, this may change as more recent developments, such as the SPiCT model (for which some aspects of stochasticity are considered in reference point calculations), become more widely used in ICES.

***Nephrops* stocks assessed in underwater TV (UWTV) surveys**

The assessments of most *Nephrops* stocks in category 1 are based on abundance estimates from underwater TV (UWTV) surveys. No stock–recruitment relationships can be estimated from these assessments and, therefore, it is not possible to calculate PA or MSY reference points using the standard ICES framework described in this document. Whereas no precautionary reference points have been defined for *Nephrops* stocks, MSY reference points are calculated as described below.

F_{MSY} is defined as a harvest rate (applied to the abundance estimate), and is derived from a deterministic equilibrium per-recruit analysis using length-structured models. The harvest rate corresponds to "dead removals" (*Nephrops* mortality due to the fishery, i.e. landings and discards assumed not to survive the discarding process). $F_{0.1}$, F_{max}, and $F_{35\%SPR}$ harvest rates based on a per-recruit analysis are considered as potential F_{MSY} (harvest rate) reference points. A stock-specific choice among them is carried out based on the criteria in the following table.

		Burrow density (average individuals m^{-2})		
		Low < 0.3	Medium 0.3–0.8	High > 0.8
Observed harvest rate or landings compared to stock status (historical performance)	> F_{max}	$F_{35\%SpR}$	F_{max}	F_{max}
	F_{max}–$F_{0.1}$	$F_{0.1}$	$F_{35\%SpR}$	F_{max}
	< $F_{0.1}$	$F_{0.1}$	$F_{0.1}$	$F_{35\%SpR}$
	Unknown	$F_{0.1}$	$F_{35\%SpR}$	$F_{35\%SpR}$
Stock-size estimates	Variable	$F_{0.1}$	$F_{0.1}$	$F_{35\%SpR}$
	Stable	$F_{0.1}$	$F_{35\%SpR}$	F_{max}
Knowledge of biological parameters	Poor	$F_{0.1}$	$F_{0.1}$	$F_{35\%SpR}$
	Good	$F_{35\%SpR}$	$F_{35\%SpR}$	F_{max}
Historical fishery	Stable spatially and temporally	$F_{35\%SpR}$	$F_{35\%SpR}$	F_{max}
	Sporadic	$F_{0.1}$	$F_{0.1}$	$F_{35\%SpR}$
	Developing	$F_{0.1}$	$F_{35\%SpR}$	$F_{35\%SpR}$

As there can be strong differences in relative exploitation rates between sexes, three values for each of the candidate reference points are determined: for each sex separately and for the two sexes combined. The combined-sex F_{MSY} is chosen, unless the resulting percentage of virgin spawner-per-recruit (%SPR) for males or females falls below 20%. In such a case, a more conservative sex-specific F_{MSY} value should be chosen over the combined-sex one.

MSY $B_{trigger}$ is typically set at the lowest stock abundance estimated historically, unless the stock has shown signs of stress at higher abundance, in which case a higher value should be used. For some *Nephrops* stocks with a short UWTV survey time-series, MSY $B_{trigger}$ has been set based on the 5^{th} percentile of a normal distribution, fitted to the observed stock abundances.

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