# A decision tool for the selection of methods to obtain indicators and reference points for data-limited stocks 

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#### Abstract

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This study was carried out in the context of the new provisions of the Fisheries Act of the Canadian Department of Fisheries and Oceans adopted in 2019 for the management of fisheries which include the implementation of measures to maintain large stocks of fish at least to the level necessary to ensure resource sustainability. In this context, an integrated fisheries management framework that relies on benchmarks linked to indicators of the state of stocks and ecosystems must be defined for each resource fished. However, several fish stocks assessed by the ministry are data-limited and the use of an analytical catch-at-age model is therefore not possible. To address this issue, a decision support tool is proposed in this document in order to provide a framework on which those responsible for evaluating the resource can rely. The tool offers a decision-making process to identify a combination of methods to describe the state of the stock according to the available information on the fishery, the population and the biology of the species. These methods are applicable in different data-limited situations so that the fish stocks provisions of the Fisheries Act can be met within the recommended timeframes.


## RÉSUMÉ

Boudreau, M. \& Duplisea, D. 2022. A decision tool for the selection of methods to obtain indicators and reference points for data-limited stocks. Can. Manuscr. Rep. Fish. Aquat. Sci. 3237: vi +61 p .

Cette étude a été réalisée dans le contexte des nouvelles dispositions de la loi sur les pêches du ministère canadien des Pêches et des Océans adoptées en 2019 pour la gestion des pêches qui comprennent la mise en œuvre des mesures pour maintenir les grands stocks de poissons au moins au niveau nécessaire pour favoriser la durabilité de la ressource. Dans ce contexte, un cadre de gestion intégrée des pêches qui s'appuie sur des points de références liés à des indicateurs de la santé des stocks et des écosystèmes doit être défini pour chaque ressource pêchée. Cependant, plusieurs stocks de ressources marines évalués par le ministère présentent un certain degré de pauvreté en données et l'utilisation d'un modèle analytique des prises par âge n'est donc pas possible. Pour répondre à cette problématique, un outil d'aide à la décision est proposé dans ce document afin d'offrir un cadre de référence sur lequel les responsables d'évaluation de la ressource peuvent s'appuyer. L'outil propose un processus décisionnel afin d'identifier une combinaison de méthodes permettant d'obtenir des indicateurs de la santé de la ressource en fonction des informations disponibles sur les pêches, la population et l'espèce. Ces méthodes sont applicables dans différentes situations de données limitées de sorte que les dispositions sur les stocks de poissons de la Loi sur les pêches puissent être respectées selon les délais recommandés.

## 1. INTRODUCTION

Following several consultations with Canadians, including representatives of the fishing industry and Indigenous peoples, the Department of Fisheries and Oceans Canada (DFO) tabled Bill C68 in June 2018, which sought to amend the Fisheries Act in Canada (RSC (1985), c. F-14) and the new provisions of which were incorporated into the Act in 2019. The various proposed amendments aim to improve the protection of fish and their habitat as well as to ensure the sustainability of marine resources for future generations. According to article 6.1 of the new law, the minister must implement, in his fisheries management, measures to maintain large fish stocks at least at the level necessary to promote the sustainability of stocks, taking into account the fish biology and the environmental conditions. In addition, section 6.2 states that the Minister shall develop and implement recovery plans for stocks that have declined to their critical zone. To respond to these new provisions, DFO has developed a batching process. For several stocks, these indicators and reference points are already determined from complex age-based models. However, the application of this type of model requires knowledge of the species biology, data on fish catch and composition, and an index of stock size and composition. For stocks that do not have enough data to fit these kinds of models, or due to a lack of resources or expertise, several less demanding methods have been developed in order to obtain stock status indicators and reference points. The use of these methods is a practical approach to meet the reference point deadlines established for DFO stocks.

This document presents methods that could be used in different contexts of data availability so that the fish stocks provisions of the Fisheries Act can be met. We provide practical advice, examples, and links to key references and programs that can be used by the department stock assessors to help meet these needs.

### 1.1 Indicators and reference points used in fishery management

An indicator represents a quantitative or qualitative value, a variable, a signal or an index from which it is possible to describe the phenomena observed in the field of fisheries (FAO 2001). The spawning stock biomass (SSB), that is, the biomass of individuals who participate in reproduction and contribute to the population renewal, is an indicator frequently used to obtain stock status (Thorson et al. 2012; Jayasinghe et al. 2017). It can provide information on the quantity of breeding individuals necessary to ensure a constant renewal of the population in addition to allowing sustainable exploitation of the resource. Variations or the trend observed in an estimated indicator over several years can also provide information on stock status (Bark, Williams and Knights 2007, Rice et al. 2015). For example, the observed trend in the number and weight of individuals caught per unit effort in commercial fisheries or in scientific surveys may indicate whether the stock size is increasing, stable or decreasing. Stock status indicators may be used to define reference points by identifying levels corresponding to a status deemed desirable, for example, a value that oscillates around a target reference point. The values of these indicators can also be used to identify an undesirable stock state such as below a limit reference point.

Two indicators frequently used to determine target and limit reference points are the stock biomass $(B)$, which is the total weight of all individuals in a stock, and the fishing mortality rate $(F)$, which represents the proportion of individuals caught by the fishery each year. Examples of
target reference points are the values of $B$ and $F$ corresponding to the maximum sustainable yield of the stock (MSY), hereafter $B_{\mathrm{MSY}}$ and $F_{\mathrm{MSY}}$ (Tsikliras and Froese 2019). $B_{\mathrm{MSY}}$ is the stock biomass that produces the maximum population growth rate. $F_{\mathrm{MSY}}$ represents the maximum proportion of individuals removed by the fishery that results, over the long term, in stock biomass of $B_{\mathrm{MSY}}$. Thus, values of $B$ that are higher or equal to $B_{\text {MSY }}$ would indicate that the stock is healthy. For many stocks in Canada, a proportion of $B_{\mathrm{MSY}}$, for example 0.8, is often used to define an upper stock reference point above which the stock is considered healthy (MPO 2019a; Marentette, Kronlund and Cogliati 2021). On the other side, a value of $F$ higher than $F_{\text {MSY }}$ would indicate that the fishing mortality rate would cause a decrease in the stock biomass over a long period of time. An example of a limit reference point is the level of stock biomass below which reproduction and population renewal have a high probability of being impaired, hereafter $B_{\text {lim. }}$. For some stocks, this limit value corresponds to the lowest value of B observed before a recovery of the population (ICES 2019). In other cases, a proportion of $B_{\mathrm{MSY}}$, for example 0.4 , is used to identify a limit reference point below which population renewal would be compromised.

### 1.2 A selection of methods according to the type of data available

In a stock assessment process, different methods can be used to obtain indicators and reference points to guide the actions needed to achieve the management objectives. The most appropriate methods will be species and fishery context specific and use magnitude (biomass and removal) and composition (length or age) data that are fishery dependent and independent. The number of types of fishing gear used during a fishing season or the length frequency of individuals in commercial catches are examples of fishery-dependent data. Spawning stock biomass and egg density estimated from a scientific survey are considered fishery independent data.
Different categories of stocks are defined in the literature according to the richness of available data (Restrepo and Powers 1999). A stock is considered data-rich when information on the population trends, the composition of individuals from different ages or lengths, and the level of exploitation is sufficient to estimate a maximum level of commercial catch that ensures maximum sustainable yield. These values can be obtained by fitting an analytical model which makes it possible to determine fishing mortality as well as the contribution of the different age classes to recruitment in the fishery and the spawning biomass. The age-structured models presented by Martell, Pine and Walters (2008) are examples of an analytical model used for data-rich stock assessment. Conversely, a stock is considered data-limited if the available information does not allow the use of this type of analytical stock assessment model. For these stocks, several methods that require less data are proposed in the literature (Newman et al. 2015; Chrysafi and Kuparinen 2016; Dowling et al. 2019; Chong et al. 2019; Pons, Cope and Kell 2020) in order to obtain stock status indicators and reference points from statistical analyses or simplified models of population dynamics.

### 1.3 Objectives

The objectives of this study are:

1) to define different categories of data-limited stocks (DLS) according to the available data;
2) identify less data-intensive methods for estimating stock status indicators and reference points;
3) provide a decision-making process to facilitate the identification of methods that can be used depending on the stock category;
4) to test functions developed with the R software for the different methods;
5) to structure the results obtained for different indicators and reference points from the methods in order to facilitate the selection of the most appropriate ones to fulfill the objectives of the Fisheries Act in relation to the sustainability of fish stocks.

Various reviews of methods requiring less data are already available in the literature. Our approach is not to replicate these reviews, but to adapt the content to the specific needs arising from changes to the Fisheries Act 2019. This technical report includes an up-to-date list of publicly available methods and codes accompanied by concrete examples relevant to the challenges of stock assessments in Canada.

## 2. DATA-LIMITED STOCKS CATEGORIES

The International Council for the Exploration of the Sea (ICES 2019) and the United States National Oceanic and Atmospheric Administration (NOAA, Newman et al. 2015; Reuter et al. 2010) distinguish between different data-limited stock categories depending on the data available. This process allows resource assessors to determine which methods might apply to their stock. Although DFO does not make such distinctions, we have defined four categories (A, B, C, D) here to facilitate the decision process for data-limited method (Figure 1).

All DLS categories must have at least a time series of commercial landings as available data in order to apply the methods in this report. The most data-rich category of DLS is DLS-A. Stocks in this category have time series of commercial landings, stock abundance indices, estimated from scientific surveys or the fishery, and length frequency in the catch. The Greenland halibut (turbot) in the Gulf of St. Lawrence is an example of DLS-A stock (DFO 2019a). DLS-B stocks are characterized by the availability of commercial landings and a stock abundance index time series, as well as the absence of length frequency data from the fishery. Examples of DLS-B stocks are the blue ling stock off East Greenland and Iceland (ICES 2018), and the Atlantic halibut stock in the Gulf of St. Lawrence (DFO 2019b). Stocks in the DLS-C category have data on commercial landings and length frequency in the catch, such as the capelin stock in the Gulf of St. Lawrence (DFO 2018). DLS-D stocks have commercial landings time series as the only available information. These categories are inclusive and although a stock is described by one category, it has the information necessary to use the methods of a less data-rich category.

## 3. SELECTION OF METHODS ADAPTED TO DATA AVAILABILITY

Literature reviews that present the applications and limitations of methods requiring less data (Chong et al. 2019; Dowling et al. 2019; ICES 2019; Pons, Cope and Kell 2020) have identified the methods frequently used to obtain stock status indicators and reference points, and for which implementations exist written in the R programming language. A directory describing each method presented in this report and links to their implementations in the R language are presented in the

Tables 1 and 2, respectively. Some methods are not presented in this report due to the lack of an available implementation but may still be appropriate for obtaining indicators and reference points. To guide the selection of one or more methods applicable to the available data and known information on a stock, different decision support schemes are proposed for each DLS category (Figures 2 to 5). In the decision-making process, the prioritization of the different methods depends on the amount of information available since fewer assumptions are required for their use. Thus, the methods that we propose to test first consider a better knowledge of the biological processes that characterize the dynamics of a stock. The different methods provide several results that provide information on different components of the stock dynamics so that the combination of several methods can be recommended to obtain stock status indicators and reference points. A total of 22 different methods were associated with DLS categories. Descriptive sheets that detail the information required, the indicators and/or reference points obtained, the assumptions, examples of results, as well as the limitations and biases associated with the application of some of these methods are presented in the appendix. A complete directory of fact sheets for each of the 22 methods is also available on GitHub.

### 3.1 Category DLS-D : Commercial landings time series only (Figure 2)

Stocks in the DLS-D category have only a time series of commercial landings and some information on the species biology or the stock dynamics. With five or more consecutive years of landings data, temporal trends can be characterized as stable, decreasing or increasing by fitting a regression line to the available data. However, these analyses must account for variations in the fishing effort or assume that it was constant. If a time series of landings is available since the beginning of the exploitation and the age at maturity and the natural mortality are known, the depletion-based stock reduction analysis (DB-SRA) is a method that can be used to obtain indicators of stock status, such as the $B / B_{\text {MSY }}$ ratio, or reference points, such as $B_{\text {MSY }}$. If the age at maturity is not known, the depletion-corrected average catch (DCAC) can be used to obtain a reference point that indicates the amount of commercial landings corresponding to the maximum sustainable yield. If the level of depletion is the only information available on the population, the scalar approach (SP) can be tested to obtain a reference point for the amount of commercial catch that is sustainable in the short term. For example, a proportion of the average value of the commercial landings over a series of years when the stock did not appear to be in decline could serve as a reference point for a sustainable level of exploitation. If commercial landings time series and natural mortality are the only information available, the optimized catch-only model (OCOM), which uses the same assumptions as a surplus production model, can be used to derive indicators of stock status, such as the level of depletion which corresponds to the ratio of $B$ to biomass in the absence of fishing ( $B_{0}$ ), and reference points, such as $B_{\text {MSY }}$ and $F_{\text {MSY }}$. Finally, if the commercial landings time series is the only available information, the boosted regression tree model (BRT) and the commercial catch ratio ( $C / C_{\text {max }}$ ) methods can be used to obtain respectively quantitative or qualitative stock status indicators. The BRT method provides a time series of the stock depletion and the $B / B_{\text {msy }}$ ratio. BRT uses a reinforced decision tree learning methods based on regressions to parameterize a statistical model that attempts to estimate the value of $B / B_{0}$ from several explanatory variables derived from commercial landings data. Qualitative indicators can also be obtained by using the $C / C_{\text {max }}$ method which makes it possible to identify different predefined stock states (underdeveloped, developing, exploited at full capacity, overexploited or depleted) according to the commercial catches ratio during the time series used.

### 3.2 Category DLS-C : Landings and catch composition but no abundance index (Figure 3)

The recent and historical trends method can again be used to determine whether the stock is increasing, stable or declining when the time series of commercial landings has at least 5 consecutive years. We suggest testing the simple stock synthesis (SSS) if the different information available makes it possible to fit the model used in this method. SSS employs a simplified approach of stock synthesis analysis which is an assessment method for data-rich stocks. SSS uses a variety of information about species life history traits and population dynamics to obtain indicators of stock status, such as time series of $B / B_{0}$ and $B / B_{\text {MSY }}$ ratios, as well as reference points like $B_{\text {MSY }}$. If the length-weight relationship, the age at maturity, the somatic growth and the catch-at-age are known, the catch-curve stock reduction analysis (CC-SRA) can be used. CC-SRA makes it possible to obtain variables such as the recruitment in the absence of fishing $\left(R_{0}\right)$ and $B_{0}$ which are then used to estimate indicators of stock status, for example, current recruitment in relation to $R_{0}$ or current biomass in relation to $B_{0}$. Then, if the length-weight relationship, the natural mortality and the length at maturity are the only information available, a series of methods that attempt to fit a simplified age-structured population dynamics model using lengths in the commercial fisheries can be tested to obtain stock status indicators and reference points. First, the length-based Bayesian biomass estimation (LBB) method uses lengths in the fishery to parameterize a population dynamics model by Bayesian inference and produces values of asymptotic length, length at first catch, as well as relative rates of natural and fishing mortality. These values are then used to estimate the $B / B_{0}$ ratio from simplified versions of stock dynamic equations. The length-based spawning potential ratio (LB-SPR) method uses changes in fishing mortality rate observed at the right side of the length-frequency curve in the commercial fishery to estimate the corresponding egg production by transforming the lengths into fecundity values. The egg production associated with the different levels of exploitation can then be compared with that obtained in the absence of fishing and thus establish reference points that ensure sufficient renewal of the population. Since the changes are only noticeable when the fishing mortality rate and the level of depletion are medium to high, LB-SPR will perform less well than LBB for stocks showing a low level of depletion (Pons, Cope and Kell 2020). Finally, LIME is another modelling method that can be used when at least one year of length composition in the fishery is available and the length-weight relationship, the length at maturity and the natural mortality are known. One of the advantages of this approach is the estimation of reference points such as $B_{\text {MSY }}$ and $F_{\text {MSY }}$ in addition to important stock status indicators such as $F$ and the spawning potential ratio (SPR).

If these three methods cannot be employed due to lack of species information, ICES and Froese length indicators are two methods to consider for obtaining stock status if the asymptotic length and the length at maturity are known. First, the ICES length indicators method uses the length frequencies of specimens in the fishery to estimate different indicators and compare them to reference points related to conservation, optimal yield and expected length distribution in a population at maximum sustainable yield. Among these indicators, there is the average length of individuals that correspond to $5 \%$ of the longest ( $L_{\text {max } 5 \%}$ ), the length corresponding to the 95 th percentile of the length frequency ( $L_{95 \%}$ ), the length corresponding to $50 \%$ of the modal abundance $\left(L_{c}\right)$, the average length of individuals $>L_{c}$ ( $L_{\text {mean }}$ ) and the length class that corresponds to the maximum biomass in commercial catches ( $L_{\text {maxy }}$ ). The other method, Froese
length indicators, uses length frequencies in the fishery to estimate indicators of health of different variables influencing sustainable population renewal, such as the proportion of mature individuals ( $P_{\text {mat }}$ ), the proportion of individuals at optimum length ( $P_{\text {opt }}$ ) or the proportion of mega-spawner individuals $\left(P_{\text {mega }}\right)$. If information on the length at maturity is not available but parameters that describe somatic growth are known, the mean length total mortality (MLZ) and the length converted catch-curve analysis (LCCC) are two methods to consider. MLZ uses a maximum likelihood approach to determine the year and total mortality $(Z)$ values that make the mean lengths predicted by a nonequilibrium Beverton-Holt equation best fit a time series of lengths in fishing. LCCC uses a linear regression applied to the descending portion of the logarithm curve of the number of individuals caught according to the lengths in the fishery converted into age classes to estimate a rate of decline in the number of fish for different age groups simultaneously. The application of these methods makes it possible to obtain the instantaneous rate of total mortality which represents the sum of the rates of natural mortality $(M)$ and fishing mortality $(F)$. From this relationship, it is possible to obtain a time series of fishing mortality rates and to estimate an average of these estimates during a reference period when fishing has not caused any negative effect on the population to obtain a proxy of $F_{\text {MSY }}$.

Less data-intensive methods that use lengths in the commercial fishery assume that the length data is representative of the composition of individuals of different sizes in the population. When this assumption is not met, methods that use time series of commercial catches to parameterize a simplified model of population dynamics can be used. If the level of stock depletion, the natural mortality and the age at maturity are known, DB-SRA provides time series of indicators and reference points such as the $B / B_{0}$ ratio and $B_{\text {MSY }}$. The OCOM, Catch-MSY and CMSY methods can also be used to obtain estimates of $B / B_{\mathrm{MSY}}, F / F_{\mathrm{MSY}}, B_{\mathrm{MSY}}$ and $F_{\mathrm{MSY}}$ when information on the level of depletion and population dynamics is known.

### 3.3 Category DLS-B : Landings and abundance index but no catch composition (Figure 4)

As with other DLS categories, the recent and historical trends method can be used to determine whether the stock is increasing, stable or declining when commercial catches and abundance indices have been available for at least 5 consecutive years. Among other methods requiring less data that can be used, SSS can be tested if the level of stock depletion, the natural mortality, the age and length at maturity, the somatic growth, the length-weight relationship and the maximum age are known. Then, the DB-SRA method can be tested if the available data (commercial catches) and the known information on the stock (level of depletion, natural mortality and age at maturity) allows it. If the natural mortality and the age at maturity are unknown, but information on population dynamics, including the intrinsic rate of increase $(r)$ and the theoretical carrying capacity ( $K$ ), are available, the Catch-MSY, CMSY and JABBA methods can be used to obtain indicators like $B / B_{\text {MSY }}$ and $F / F_{\text {MSY }}$ ratios as well as reference points like $B_{\text {MSY }}$ and $F_{\text {MSY }}$. If no information is available on the level of stock depletion, the method that uses a stochastic surplus production model in continuous time (SPiCT) can be employed to obtain stock status indicators and reference points similar to Catch-MSY, CMSY and JABBA. This latter method attempts to fit a Pella-Tomlinson state-space surplus production model that incorporates observation errors in commercial catches and abundance indices, as well as process errors associated with fishing
and population growth. If none of the above methods can be used, the DCAC, SP, or OCOM methods can be used when the level of depletion and/or the natural mortality is known. If the latter information is not available but the biomass of the stock is known, the average of the biomass estimated during a reference period during which fishing did not cause a negative effect on the population can be used to get a proxy for $B_{\text {MSY }}$. Similarly, estimating the average exploitation rate (catch/biomass) over a reference period where fishing has not caused a decline can also provide a proxy for $F_{\text {MSY }}$. Finally, if the stock biomass cannot be estimated, the BRT and $C / C_{\text {max }}$ methods can be used to obtain quantitative or qualitative indicators of stock status.

### 3.4 Category DLS-A : Landings, catch composition and abundance index (Figure 5)

Since this category of stocks is the one with the greatest amount of information, several methods proposed for the DLS-B, DLS-C and DLS-D categories can be used to obtain stock status indicators and reference points. Estimates of abundance indices, in particular the average weight per unit effort in scientific surveys, can be used to determine whether the stock is increasing, stable or decreasing based on the recent and historical trends method. Then, depending on the information available on the species life history traits, the level of depletion and the population renewal, several methods that use simplified models to describe the stock dynamics should be considered. The SSS method makes it possible to obtain time series of the $B / B_{0}$ and $B / B_{\mathrm{MSY}}$ ratios, as well as reference points like $B_{\text {msy. }}$. If the length-weight relationship, the age at maturity, the somatic growth and the catch-at-age are known, the CC-SRA method can also be used to obtain stock status indicators such as the current recruitment relative to $R_{0}$ or the current stock biomass relative to $B_{0}$. If length composition in the fishery is available and the length-weight relationship, the natural mortality and the length at maturity are known, the LIME, LB-SPR and LBB methods can be used to obtain stock status indicators and reference points such as the SPR, $B_{\text {MSY }}$ and $F_{\text {msy }}$. Other methods that use length composition in the fishery and require less information on life history traits can also be used. The ICES length indicators provide reference points related to conservation, optimal yield and the distribution of expected lengths in a population at maximum sustainable yield, while the Froese length is an indicator of the health of some variables affecting population renewal. The MLZ and LCCC methods that estimate an instantaneous rate of total mortality $(Z)$ from length time series in the fishery can be used to derive a proxy for $F_{\text {MSy }}$ from the equation $Z=M+F$, which relates the total mortality, the natural mortality and the fishing mortality.

As with the DLS-C stock category, if length data cannot be used, methods that use information on population dynamics to fit a simplified biomass surplus production model can be employed to obtain different stock status indicators ( $B / B_{\mathrm{MSY}}, B / B_{0}$ and $F / F_{\mathrm{MSY}}$ ) and reference points ( $B_{\mathrm{MSY}}$ and $F_{\text {MSY }}$ ). DB-SRA can be used if the level of depletion, the natural mortality and the age at maturity are known, while Catch-MSY, CMSY and JABBA should be considered if the mortality and the age at maturity are unknown but the intrinsic rate of increase and the theoretical carrying capacity are available. The SPiCT method can also be tested if information on stock dynamics is known and the incorporation of observation and process error is appropriate. Finally, $B_{\text {MSY }}$ and $F_{\text {MSY }}$ proxies can be estimated if no information on the population dynamics and the species life history traits is available, but the stock biomass is known. The $B_{\text {MSY }}$ proxy is obtained by calculating the average of the stock biomass estimates during a reference period during which fishing has not caused a negative effect on the population, while $F_{\text {MSY }}$ is derived from the average of the ratio
between the catches and the stock biomass estimates over a similar period of stability in stock health.

## 4. METHOD APPLICATIONS FOR DIFFERENT GROUPS OF FISH SPECIES

Depending on the information available on the exploitation of a stock and on the biology of the target species, it is possible that several data-limited methods can be employed to obtain stock status indicators and reference points. In order to show the versatility of the proposed methods, their applications have been listed for different groups of fish species (Table 3). In addition, the proposed methods were tested with the information available on the Greenland halibut, the Atlantic halibut, the capelin and the American plaice stocks in fishing areas 4R, 4S and 4T of the Northwest Atlantic Fisheries Organization (NAFO). Several examples of method applications which describe the information required, the mechanics of the method, the indicators and/or the reference points obtained, the assumptions, the limitations and the sources of bias are presented in Appendices 1 to 13. The functions programmed in the $R$ language that led to the results presented in the appendices are available at https://github.com/MathBoud/DLM.ReferencePoint.

Although some literature reviews and scientific articles present and compare the use of several of the proposed methods (Chong et al. 2019; Dowling et al. 2019; ICES 2019; Pons, Cope and Kell 2020), it is up to those responsible for the assessment of the resource to determine those that are appropriate to the assumptions and limitations of the methods, the biology of the species being assessed, and the knowledge of the manager. The decision-making processes developed here propose to test different methods depending on the origin and the nature of the available data on a stock. These processes do not assume that one method is better than another but rather that certain methods can be used depending on the available data and known information about a species.

## 5. THE INVERTEBRATES : A SPECIAL CASE

The different methods proposed in the previous sections are mainly used to assess the health of fish stocks with limited data. These methods, especially those that use population dynamic models, seem to be less used to assess invertebrate stocks (Caddy 2004, Smith and SainteMarie 2004), even if some of them have that potential. However, invertebrates form the basis of the most productive fisheries in Canada and they often have unique biological characteristics that pose different challenges compared to fish when fitting a population dynamics model. For example, determining the age of invertebrate specimens is often more difficult to perform, so this type of compositional data is rarely available. Invertebrates also possess a long growth phase as drifting pelagic larvae before settling on the bottom and their stock-recruitment dynamics are often non-local. Some species, such as the northern shrimp (Pandalus borealis), are protandrous hermaphrodites, that is, they grow and reach sexual maturity as males, then spend the rest of their reproductive life as females. The difficulty in determining the age of species that molt seasonally, such as the snow crab (Chionoecetes opilio) and the American lobster (Homarus americanus), can complicate the study of population structure and therefore the identification of an adequate level of exploitation above a certain size. Some environmental factors, notably water temperature, tidal range or prey density, can greatly influence the productivity of a stock,
particularly for sessile invertebrate species such as bivalves (Bivalvia), or with reduced mobility such as sea cucumbers (Holothuroidea).

In order to facilitate the work of those responsible for evaluating the resource, the different indicators and reference points proposed in literature reviews (Gilbert, Annala and Johnston 2000; Caddy 2004) have been identified and associated with three main categories of invertebrates: crustaceans, molluscs and bivalves, and organisms with reduced mobility. These categories are described in the work carried out by Smith and Sainte-Marie in 2004. The objective of this work was to propose relevant indicators for the development of reference points for different groups of invertebrates. These categories are defined according to the developmental stages, the reproductive behaviour and the mobility of adults. A first category, the crustaceans, includes species of invertebrates, such as crabs, lobsters and shrimps, whose adults are mobile, the reproduction rate is high, the individuals show significant sexual size dimorphism and the females brood their eggs. In the species of the second category, namely molluscs and bivalves, reproduction takes place following the release of a large quantity of gametes into the water by reproductive adults who are sessile. Species whose adults have reduced mobility and reproduction takes place in the water column, such as the sea cucumber or the sea urchin, are found in the last category of invertebrate.

### 5.1 Invertebrate stock status indicators

The work of Gilbert, Annala and Johnston (2000) and that of Caddy (2004), makes it possible to draw up a list of the different variables that we suggest should be considered in the development of indicators to assess the status of an invertebrate stock (Table 4). These different variables have been associated with four groups of factors that can influence stock status: abundance, productivity, fishing pressure and the environment. Many of the methods suggested for the different DLS categories above may be applicable to invertebrates, but one should be aware of species and stock features before using them.

### 5.1.1 Indicators of abundance

First, abundance indicators can be estimated from the available information of commercial fishing and scientific surveys. The mean number of individuals caught per unit effort as well as the total area with good density of specimens can be used in the three categories of invertebrates and serve to develop reference points. For example, the average value of the mean number per unit effort during a period when the stock biomass and the commercial landings were stable can be used as a target reference point. A minimum value of the area with high specimen density can also be used to define a limit reference point. Another indicator of abundance proposed in the literature for crustacean stocks that are not subject to directed fishing is the amount of bycatch landings in the fishery directed towards other species (Caddy 2004). A limit reference point can also be defined from this variable. It would indicate the maximum amount of bycatch for a population capable of long-term renewal.

### 5.1.2 Indicators of productivity

Then there are the indicators that provide information on the productivity of a population. Those that may apply to all three groups are the number of recruits in scientific surveys, the area with a
high density of recruits, the mean size of adult females and the condition factors. For the establishment of reference points, minimum values for the number of recruits or the area with high density of recruits which ensures the maintenance of the population at a level deemed to be sustainable can in particular serve as a limit reference. A mean female size that maximizes egg productivity can also be used as a target reference point. A limit reference point can also be developed by establishing the minimum value of a condition factor. Values below this limit reference point would indicate that the exploitation is not sustainable. There are also indicators of stock productivity that are more specific to certain groups of invertebrates. The density of larvae (number $/ \mathrm{m}^{2}$ ) in the water column sampled during scientific surveys can provide information on the productivity of different mollusc and bivalve beds in a fished sector and possibly establish a limit exploitation level on higher productive beds. The sex ratio and the proportion of berried females to non-berried females can provide an index of fecundity in crab and lobster populations and possibly an index of the exploitation rate (Bennett 1974).

### 5.1.3 Indicators of fishing pressure

The total mortality rate estimated from the lengths in the scientific surveys, the number of fishing days of a fleet per season, the percentage of immature individuals as well as the amount of gear per fishing area are indicators of fishing pressure on a population. Some can be used to develop reference points. For example, a mean total mortality rate estimated during a period when fishing would not have had an impact on the health of the population can serve as a target reference point. Recommendations aimed at reducing the level of withdrawal can then be issued when this target reference rate is exceeded. A percentage of immature individuals can also be used as a target reference point and indicates the level that should not be exceeded to ensure a sufficient number of mature individuals to allow the sustainable renewal of the population. A more specific indicator for shrimps of the Pandalidae family is the sex ratio. This variable provides information, among other things, on the mortality rate in the population resulting from fishing, which mainly targets females (Hannah and Jones 1991). This variable can be used to establish a target reference point for the exploitation level of a stock.

### 5.1.4 Indicators of the environment

The last list of indicators includes those that provide information on the state of environmental characteristics that can influence the health of invertebrate stocks. The predator-prey abundance ratio, the prey density (number $/ \mathrm{m}^{2}$ ), the percentage of good quality habitat, and the difference between the habitat temperature and the optimum temperature, are variables that can be used for the three groups of invertebrates proposed. Even if management measures such as a reduction in landings do not change the trend of all these indicators, reference points can still be established to guide certain decisions. The reduction of fishing activities can, in particular, be recommended in a sector where the environmental conditions are unfavourable for the species, such as a large difference between the habitat temperature and the optimum temperature, or an increase in the abundance of a predator. In this case, a limit value beyond which a reduction in fishing pressure is recommended can be established from the predator-prey abundance ratio or the difference between the temperature at the bottom and the optimum temperature.

## 6. EXAMPLE OF DATA-LIMITED STOCK ASSESSMENT FOR CAPELIN AND SUGGESTED PRESENTATION OF RESULTS

### 6.1 Determine the methods to test

The various diagrams and tables proposed in the previous sections make it possible to identify one or more methods suited for the available data to obtain stock status indicators and reference points for a population subjected to fishing activities. In some cases, several indicators or reference points, such as $B / B_{\mathrm{MSY}}, F / F_{\mathrm{MSY}}, B_{\mathrm{MSY}}$ and $F_{\mathrm{MSY}}$, can be obtained following the application of the proposed methods. Multiple methods may also be appropriate for the available data and may produce different values for the same indicator or reference point. The comparison of these different results makes it possible to consolidate the variations observed in the variables predicted by the models, such as the stock biomass, and to check the level of confidence in the estimates obtained using the associated precision measurements. The decision-making process presented in Section 3 was tested for the capelin stock fished in NAFO fishing areas 4R, 4S and 4T. The available data for this stock are time series of total annual landings and composition of individuals caught in the fishery. Using the decision-making process shown in Figure 1, this capelin stock was assigned to the DLS-C category. Although data on lengths in the commercial fishery are collected each year, they were not available at the time of our analyses. For this reason, the LIME, LB-SPR, LBB, ICES lengths, Froese lengths, MLZ and LCCC methods have not been tested. The CC-SRA method was also not considered due to the lack of information on catch-at-age. The methods that were finally applied are SSS, OCOM, DB-SRA and CMSY since the necessary information was available (level of depletion, natural mortality, length and age at maturity) or could be assumed from the fact sheet on capelin in FishBase such as somatic growth, length-weight relationship (Froese, Thorson and Reyes Jr. 2014) and population dynamics (Froese et al. 2017).

### 6.2 Structuring the obtained results

Once the different methods were tested, the results could be structured in the form of a summary table in order to facilitate the selection of the most appropriate method to meet the objectives of the Fisheries Act in relation to the sustainability of fish stocks. This type of table presents information on the indicators or reference points chosen, the estimated value and its associated error, as well as the performance of the approach, which is determined by the fit of the models used and the precision of the results obtained. A qualitative measure that describes the appreciation of the specialists responsible for assessing the stock with regard to the methods applied is also included in this summary table. This different information is then used to consolidate the acceptance or rejection of the indicators and reference points obtained from the methods that have been tested. Thus, the SSS, OCOM, DB-SRA and CMSY methods applied to available data and known information on the capelin stock in NAFO fishing areas 4R, 4S and 4T have made it possible to obtain different values for the points reference $B_{\text {MSY }}$ and $F_{\text {MSY }}$ (Table 5). The $B_{\text {MSY }}$ values vary between 30160 and 31886 tons for all the methods tested. The values obtained for $F_{\text {MSY }}$ vary between 0.235 and 0.346 for the OCOM, DB-SRA and CMSY methods. The results obtained with the SSS and OCOM methods were deemed not acceptable due to the accuracy of the values obtained, which was less than that of the other methods, and the trajectory of the predicted stock biomass, which corresponded more or less to the biomass variations observed in the fishery. The reference points obtained with the DB-SRA and CMSY methods were
considered acceptable since the precision of the estimated values was better and the predicted biomass corresponded better to observations in the fishery.

### 6.3 Using the results to fulfill the Fisheries Act objectives

The use of the CMSY method also made it possible to produce different graphical results that facilitate the use of the indicators and the reference points obtained to fulfill the objectives of the Fisheries Act (Figure 6). First, the total annual commercial landings (Figure 6.A) were, in 2018 (8142 tons) and 2019 ( 7597 tons), within the confidence interval for the estimated MSY value ( 6864,8440 ). The predicted values in 2019 for the stock biomass to $B_{\text {MSY }}$ ratio (0.97; Figure 6.C) and for the fishing mortality to $F_{\text {MSY }}$ ratio (1.04; Figure 6.D) are very close to 1, a value that indicates that the stock is exploited at maximum sustainable yield. In addition, it is also possible to establish stock status zones from indicators and reference points, for example, using $B_{\text {MSY }}$ proportions. In this example, a limit and an upper reference points were estimated from $0.4 \times B_{\text {MSY }}$ and $0.8 \times B_{\mathrm{MSY}}$, respectively (Figure 7). Stock status is considered critical if the biomass value is below the limit reference point and healthy when the stock biomass is higher than the upper reference point. When the biomass is between the upper and limit reference points, the stock is considered in a cautious zone. Thus, the capelin stock would have been considered in the cautious zone from 2014 to 2017 before finding itself in the healthy zone in 2018 and 2019 according to the results obtained with the CMSY method (Figure 7).

Once the different indicators and reference points have been chosen to describe the status of a fished population, they can be reported in another table which is inspired by the concept of "traffic light table", also used in scientific advice produced by ICES. ICES also proposes to distinguish between two types of information in this type of summary table, namely indicators of the commercial fishery performance and the status of the stock (ICES 2019). These use a colour code and symbols that provide information on the health of a population according to the position of the values estimated for different indicators (Table 6). ICES distinguishes the indicators and reference points used according to the management objectives that follow the principles of maximum sustainable yield and a precautionary approach. Thus, this concept of structuring the results was applied to the results obtained for the capelin stock in order to demonstrate how different components of the population dynamics are used to fulfill the objectives of the Fisheries Act concerning the sustainability of fish stocks (Table 7). The stochasticity in ocean conditions and productivity regimes can also influence population dynamics. This is why a new category presenting different environmental variables whose impacts on population dynamics have been tested could be added to the summary proposed by ICES. For example, the results of a study which showed that the capelin probability of occurrence increases in warmer deep waters and that higher densities of capelin are associated with a greater number of prey, such as macro zooplankton (McGowan et al. 2019), would be included in this new category of information to be considered in the assessment. In this way, decisions relating to the establishment of an acceptable level of exploitation are based on all the factors that can impact the sustainability of a fishing stock.

## 7. DISCUSSION

### 7.1 Application of the methods to fulfill the Fisheries Act provisions

The methods presented in this technical report provide a framework for determining how fishery status, population health and reference points can be obtained for data-limited stocks. Some of these methods, particularly those that use an age-structured population model (SSS, LB-SPR) or that consider variability in recruitment and mortality (CC-SRA, SPiCT, LIME), provide results that allow to meet the objectives of the Fisheries Act regarding the sustainability of fish stocks. It is obvious that the different methods proposed do not provide indicators and reference points as robust as the methods used to assess data-rich stocks, such as sequential population analysis. Thus, their use to meet the objectives of the Fisheries Act is limited due to the lack of information allowing to properly characterize all the processes that influence the dynamics of a population. On the other hand, assigning a stock category and selecting the appropriate assessment methods could facilitate the identification of missing data for a population to change category and be assessed with methods requiring a greater amount of data information.

### 7.2 Use of stock categories in stock assessment processes

The tool proposed in this technical report is based on a categorization process based on the availability of data and knowledge on the species. Because of its benefits, this process is commonly used in other jurisdictions, including ICES (ICES 2019) and NOAA (Reuter et al. 2010), to identify recommended methods in stock assessments. First, the technical framework for the assessment is determined based on the category assigned to the stock. Second, the framework established by the stock category facilitates the selection of appropriate methods for establishing stock status indicators and reference points based on established management objectives. Finally, the identification of data and knowledge gaps is inherent in the categorization process. It therefore guides new research that can improve the quality of evaluations.

Although it provides several advantages, the categorization process is not currently used in DFO stock assessments. There is, however, a consensus of various experts regarding the relevance of considering this approach (ICES 2019). In addition, this reference framework allows other jurisdictions, such as ICES, to distinguish between the application of the maximum sustainable yield principle or the precautionary approach in the assessment of a stock according to its category. For example, recommendations for stocks in ICES categories 3 to 6 (Table 8) are based on a precautionary approach and generally include the estimation of a limit reference point (ICES 2018). Thus, the methods proposed for categories DLS-A, DLS-B, DLS-C and DLS-D, whose source of data is similar to ICES categories 3 to 6 , could satisfy the minimum requirement of a limit reference point, as prescribed by the new Canadian Fisheries Act.

In the Quebec region, only 3 stocks out of more than thirty stocks of fish and invertebrates that are the subject to assessment of their status are considered to be rich in data and have an analytical model used to guide management measures. All other stocks are associated with the different DLS categories defined in this document and a similar context exists in other regions of Canada (DFO 2021). The lack of a formal process for estimating reference points and making recommendations for these data-limited stocks reduces the ability to meet the requirements of Canadian fisheries law. The various DLS category diagrams presented in this document are an
attempt to formalize this kind of process for DFO. The application of such a process for categorizing DLS should make it possible to highlight its strengths and weaknesses in the context of stock assessments at DFO. It may need to be modified as its limitations in practice become apparent. Moreover, the process proposed in this document is a first version, which will be continuously updated with the new methods developed in the field of fishery science.

## 8. CONCLUSION

The primary objective of this study was to provide a framework for categorizing data-limited stocks that are subjected to commercial fishing and to identify methods that can be used to obtain stock status indicators and reference points to guide decisions on appropriate levels of exploitation. Interest in developing a framework such as this stems from the June 2019 enactment of the fish stocks provisions in the Fisheries Act. Decision trees for determining which methods should be applied depending on the context have been provided to demonstrate their ability to meet the objectives of the Act. Concrete examples of results obtained from certain methods have been presented in order to propose a structure to frame the selection of indicators and reference points to be used in the assessment of a stock. A summary table that provides information on fishery performance and stock status has also been proposed to demonstrate how information obtained from data-limited stock assessment methods could fulfill some of the Fisheries Act objectives for fish stocks. The continuous refinement of such an approach with a more detailed development of decision tools and the availability of a directory of codes specific to the needs of DFO would allow, in the long term, to formulate more consistent and reproducible advice.

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## 10. TABLES AND FIGURES

Table 1. Data-limited methods frequently employed to obtain stock status indicators and reference points, and are easily usable with programmed functions in $R$.

| Methods | Reference |
| :--- | :--- |
| $B_{\text {Msy proxy }}$ | Assessment of Gulf of St. Lawrence (4RST) Greenland halibut <br> (MPO 2019) |
| $F_{\text {MSY proxy }}$ | ICES Advice on fishing opportunities, catch, and effort for Blue <br> ling (Molva dypterygia) in Subarea 14 and Division 5.a (ICES <br> 2018) |
| Froese length indicators | Keep it simple: three indicators to deal with overfishing (Froese <br> 2004) |
| ICES length indicators | Technical Guidelines - ICES reference points for stocks in <br> categories 3 and 4 (ICES 2019) |
| Recent and historical trends | Second technical consultation on the suitability of the CITES <br> criteria for listing commercially-exploited aquatic species (FAO <br> 2001) |
| Catch ratio (C/Cmax) | Assessing global marine fishery status with a revised dynamic <br> catch-based method and stock-assessment reference points <br> (Anderson et al. 2012) |
| Boosted regression tree <br> (BRT) | Estimating stock depletion level from patterns of catch history <br> (Zhou et al. 2017) |
| Scalar approach (SP) | Calculating acceptable biological catch for stocks that have <br> reliable catch data only (Only Reliable Catch Stocks- ORCS) <br> (Berkson et al. 2011) |
| Depletion-corrected average | Depletion-corrected average catch: a simple formula for <br> estimating sustainable yields in data-poor situations (MacCall <br> 2009) |
| catch (DCAC) | An optimized catch-only assessment method for data poor <br> fisheries (Zhou et al. 2018) |
| Optimized catch-only model <br> Cacom) | Depletion-based stock reduction analysis: a catch-based method <br> for determining sustainable yield for data-poor fish stocks (Dick <br> et MacCall 2011) |
| A simple method for estimating MSY from catch and resilience |  |
| (Martell et Froese 2013) |  |

Table 1 (continued).

| Methods | Reference |
| :--- | :--- |
| Simple stock synthesis <br> (SSS) | Implementing a statistical catch-at-age model (Stock synthesis) <br> as a tool for deriving overfishing limits in data-limited situations <br> (Cope 2013) |
| CMSY | Estimating fisheries reference points from catch and resilience. <br> (Froese et al. 2017) |
| Just another Bayesian <br> biomass assessment <br> (JABBA) | JABBA: Just Another Bayesian Biomass Assessment (Winker, <br> Carvalho and Kapur 2018) |
| Stochastic surplus <br> production model in <br> continuous time (SPiCT) | A stochastic surplus production model in continuous time <br> (Pedersen and Berg 2017) |
| Mean length mortality <br> estimator (MLZ) | Estimating mortality from mean length data in nonequilibrium <br> situations, with application to the assessment of goosefish <br> (Gedamke and Hoenig 2006) |
| Length-converted catch <br> curve (LCCC) | Length-converted catch curve and the seasonal growth of fishes <br> (Pauly 1990) |
| A novel length-based empirical estimation method of spawning <br> potential ratio (SPR), and tests of its performance, for small- <br> scale, data-poor fisheries (Hordyk et al. 2015) |  |
| potential ratio (LBawnisPR) | Accounting for variable recruitment and fishing mortality in <br> length-based stock assessments for data-limited fisheries (Rudd <br> and Thorson 2018) |
| Length-based integrated |  |
| mixed effect (LIME) | Length-based Bayesian Biomass estimator (LBB) for data- <br> limited stock assessment (Froese et al. 2018) |
| Length-based Bayesian |  |
| Biomass estimator (LBB) |  |

Table 2. R-language implementations of the different data-limited to obtain stock status indicators and the reference points proposed in the decision-making tool.

| Methods | Library/ Function | Reference |
| :---: | :---: | :---: |
| $B_{\text {msy }}$ proxy | DLM.ReferencePoint/ Bmsy.Fmsy.Proxy.R | https://github.com/MathBoud/DLM.ReferencePoi nt/tree/master/R/Bmsy\%20\%26\%20Fmsy\%20pr oxy |
| $F_{\text {msy }}$ proxy | DLM.ReferencePoint/ Bmsy.Fmsy.Proxy.R | https://github.com/MathBoud/DLM.ReferencePoi nt/tree/master/R/Bmsy\%20\%26\%20Fmsy\%20pr oxy |
| Froese length indicators | DLM.ReferencePoint/ FroeseLengthIndicator | https://github.com/MathBoud/DLM.ReferencePoi nnt/tree/master/R/Froese\%20length\%20indicators |
| ICES length indicators | ICES_MSY/ <br> LBindicators.R | https://github.com/ices-toolsdev/ICES MSY/blob/master/R/LBindicators.R |
| Recent and historical trends | DLM.ReferencePoint/ Recent\&Historical.Tren s.R | https://github.com/MathBoud/DLM.ReferencePoi nt/tree/master/R/Recent\%20\%26\%20historical\% 20trend |
| Catches ratio ( $C / C_{\text {max }}$ ) | DLM.ReferencePoint/ CatchRatio.R | https://github.com/MathBoud/DLM.ReferencePoi nt/tree/master/R/Catch\%20ratio |
| Boosted regression tree (BRT) | datalimited2/ <br> zbrt | https://rdrr.io/github/cfree14/datalimited2/man/zb rt.html |
| Scalar approach (SP) | DLM.ReferencePoint/ ScalarCatchMethod.R | https://github.com/MathBoud/DLM.ReferencePoi nt/tree/master/R/Scalar\%20Catch\%20method |
| Depletion-corrected average catch (DCAC) | DLMtool/ DCAC | https://search.r- <br> project.org/CRAN/refmans/DLMtool/htmI/DCAC. <br> html |
| Optimized catch-only model (OCOM) | datalimited2/ ocom | https://rdrr.io/github/cfree14/datalimited2/man/oc om.html |
| Depletion-based stock reduction analysis (DBSRA) | fishmethods/ dbsra | https://rdrr.io/cran/fishmethods/man/dbsra.html |
| Catch-MSY | fishmethods/ catchmsy | https://www.rdocumentation.org/packages/fishm ethods/versions/1.11-1/topics/catchmsy |
| Catch curve stockreduction analysis (CCSRA) | CCSRA / CCSRA.R | https://github.com/James-Thorson/CCSRA |

Table 2 (continued).

| Methods | Library/ <br> Function | Reference |
| :--- | :--- | :--- |
| Simple stock synthesis <br> (SSS) | MSEtool / <br> SSS | datalimited2/ <br> cmsy2 |

Table 3. Applications data-limited methods that provide stock status indicators and reference points for different groups of fish species.

| Methods | Species | References |
| :---: | :---: | :---: |
| OCOM | Groundfish in warm waters | Zhou et al. 2018 |
| DCAC | Sebastes entomelas | MacCall 2009 |
| DB-SRA | Pacific West Coast groundfish | Dick and MacCall 2011 |
| SSS | Pacific West Coast groundfish | Cope 2013 |
| CC-SRA | Slow and periodic growing fish | Thorson and Cope 2015 |
| Catch-MSY | Greenland halibut | Martell and Froese 2013 |
| CMSY | Blue tuna | Froese et al. 2017 |
| JABBA | South Atlantic swordfish | Winker et al. 2018 |
| SPiCT | Atlantic cod | Pedersen and Berg 2017 |
| LB-SPR | Pegusa lascaris <br> Sebastes emphaeus <br> Platycephalus endrachtensis <br> Cololabis saira | Hordyk et al. 2015 |
| LIME | Siganus sutor <br> Lutjanus guttatus <br> Epinephelus morio | Rudd and Thorson 2018 |
| LBB | Cuttlefish, shrimp, anchovies, sprat, herring, flatfish, roundfish, rays and sharks | Froese et al. 2018 |
| MLZ | Lophiidae | Gedamke and Hoenig 2006 |
| LCCC | Galeoides decadactylus | Wehye and Amponsah 2017 |

Table 4. Variables proposed for the selection of relevant indicators to assess the stock status of crustaceans, mollusks and bivalves, and invertebrates with reduced mobility according to different factors that can influence the health of stocks.

| State | Indicators | Species groups |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  |  | Crustaceans | Mollusks and bivalves | Adults with lower mobility |
| Abundance | Mean number per unit of effort (fishery and scientific survey) | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Total area with high density of individuals | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Bycatch landings in directed fisheries of other species | $\checkmark$ |  |  |
| Productivity | Density of recruits (scientific survey) | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Total area with high density of recruits | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Mean length of adult females | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Condition indices | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Density of larvae in the water column (scientific survey) |  | $\checkmark$ |  |
|  | Sex ratio (fishery and scientific survey) | $\checkmark$ |  |  |
|  | Percentage of egg-bearing females (fishery and scientific survey) | Crab and lobster |  |  |
| Fishing pressure | Mean total mortality rate based on length data (scientific survey) | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Fleet days fished per season | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Percentage of immature individuals (fishery and scientific survey) | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Annual number of trap hauls per area grounds | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Sex ratio in the fishery | Shrimp Pandalidae |  |  |
| Environment | Predator-prey abundance ratio | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Prey density | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Percentage of good habitat quality | $\checkmark$ | $\checkmark$ | $\checkmark$ |
|  | Absolute value \|bottom temperature optimum temperature| | $\checkmark$ | $\checkmark$ | $\checkmark$ |

Table 5. Summary table of the reference points obtained following the application of the CatchMSY, OCOM, DB-SRA, and CMSY methods with annual landing data in the capelin commercial fishery in NAFO fishing areas 4R, 4S and 4T.

| Methods | Reference points | Estimated values | $\begin{gathered} \hline \text { Precision } \\ \text { (95\% CI) } \end{gathered}$ | Model fit | Appreciation | Decision |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| SSS | $B_{\text {MSY }}$ (tons) | 30386 | - | Average | Average | Rejected |
|  | $F_{\text {MSY }}$ | - | - |  |  |  |
|  | MSY (tons) | 7658 | - |  |  |  |
| OCOM | $B_{\text {MSY }}$ (tons) | 31634 | [17 084; 95 402] | Average | Average | Rejected |
|  | $F_{\text {MSY }}$ | 0,235 | [0.056; 0.517] |  |  |  |
|  | MSY (tons) | 7541 | [4894; 9190] |  |  |  |
| DB-SRA | $B_{\text {MSY }}$ (tons) | 31886 | [28 704; 36 687] | Good | Good | Acceptable |
|  | $F_{\text {MSY }}$ | 0,346 | [0.337; 0.350] |  |  |  |
|  | MSY (tons) | 7455 | [6709; 8591] |  |  |  |
| CMSY | $B_{\text {MSY }}$ (tons) | 30160 | [24 194; 35 797] | Good | Good | Acceptable |
|  | $F_{\text {MSY }}$ | 0,252 | [0.214; 0.297] |  |  |  |
|  | MSY (tons) | 7611 | [6864; 8440] |  |  |  |

Table 6. Symbols used to describe the performance of the commercial fishery and the health of the fished population in relation to different reference points established according to the approach that ICES uses to present a summary of the stock health and fishing status.

| Symbols | Description | Maximum sustainable yield | Temporal trends |
| :---: | :---: | :---: | :---: |
|  |  | $B_{\text {MSY }} \quad F_{\text {MSY }}$ | Abundance indices in fishery and surveys |
| $\checkmark$ | The population is exploited and renewed at maximum sustainable yield | $B=B_{\text {MSY }} \quad F=F_{\text {MSY }}$ |  |
| $\checkmark$ | The population is in the healthy zone | $B>0,8 \times B_{\text {MSY }} \quad F \leq F_{\text {MSY }}$ |  |
| - | The population is in the cautious zone | $\begin{aligned} & B<0,8 \times B_{\mathrm{MSY}} \\ & B>0,4 \times B_{\mathrm{MSY}} \end{aligned} \quad F \leq F_{\mathrm{MSY}}$ |  |
| $x$ | The population is in the critical zone | $B<B_{\text {MSY }} \quad F>F_{\text {MSY }}$ |  |
| $?$ | Unknown information | No reference point defined | No indicator |
| 7 | Increasing |  | Higher than the previous year |
| $\pm$ | Decreasing |  | Lower than the previous year |
| $\rightarrow$ | Stable |  | the same value than the previous year |

Table 7. Summary table of information used to describe fishing performance, population health and environmental conditions of the capelin stock in NAFO fishing areas $4 R, 4 S$ and $4 T$ from selected indicators and reference points based on the approach that ICES uses to present a summary of the health of a stock and the state of the fishery.

|  | Fishing status |  |  |  | Population health |  |  |  | Environmental conditions |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 2017 | 2018 | 2019 |  | 2017 | 2018 | 2019 |  | 2017 | 2018 | 2019 |
| Recent temporal trend | Total annual landings | $y$ | $\rightarrow$ | 7 | Stock biomass | $\rightarrow$ | 7 | 7 | Deep-water temperature | $\rightarrow$ | 7 | 7 |
|  |  |  |  |  |  |  |  |  | Prey density | $\rightarrow$ | $\rightarrow$ | 7 |
| Maximum sustainable yield | $F_{\text {MSY }}$ | $\checkmark$ | $x$ | $\checkmark$ | $B_{\text {MSY }}$ | - | $\checkmark$ | $\checkmark$ |  |  |  |  |

Table 8. Example of summary table used by ICES to describe stock health and fishing status in relation to different reference points for the stock blue ling in the fishing areas of East Greenland and Island.

|  |  | Fishing pressure |  |  |  | Stock size |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 2015 | 2016 |  | 2017 |  | 2015 | 2016 |  | 2017 |
| Maximum Sustainable yield | $F_{\text {Msy }}$ proxy | $\checkmark$ | $\checkmark$ | $\checkmark$ | Below | $\underset{\mathrm{B}_{\text {Trigger }}}{\text { MSY }}$ | ? | ? | ? | Undefined |
| Precautionary approach | $\mathrm{F}_{\mathrm{pa} \text {, }}$ Fim | $\checkmark$ |  | $\checkmark$ | Below possible reference point | $\begin{aligned} & \mathrm{B}_{\mathrm{paz}}, \\ & \mathrm{Blim}^{2} \end{aligned}$ | ? | ? | ? | Undefined |
| Management plan | $F_{\text {mgt }}$ | - | - |  | Not applicable | $B_{\text {MGT }}$ | ? | ? | ? | Not applicable |
| Qualitative evaluation | - | - | - | - | Not applicable | - | V | $\rightarrow$ | $\rightarrow$ | Stable |



Figure 1. Decision tree for assigning a data-limited stock (DLS) category based on the available data. Green arrow = yes. Red arrow = no.


Figure 2. Decision tree for narrowing the proposed data-limited methods to obtain stock status indicators and reference points for the DLS-D category. Green arrow = yes. Red arrow = no.


Figure 3. Decision tree for narrowing the proposed data-limited methods to obtain stock status indicators and reference points for the DLS-C category. Green arrow = yes. Red arrow = no.


Figure 4. Decision tree for narrowing the proposed data-limited methods to obtain stock status indicators and reference points for the DLS-B category. Green arrow = yes. Red arrow = no.


Figure 5. Decision tree for narrowing the proposed data-limited methods to obtain stock status indicators and reference points for the DLS-A category. Green arrow = yes. Red arrow = no.


Figure 6. Plot results obtained with the CMSY method applied to commercial landings of capelin in NAFO fishing areas 4R, 4S and 4T from 1975 to 2019. A) Time series of commercial landings and estimated mean value of MSY ( $\pm 95 \%$ CI). B) Viable r-K pairs used to predict the stock biomass that can support the observed commercial landings. C) Time series of the mean biomass value ( $\pm 95 \%$ CI) predicted by the model to $B_{M S Y}$ ratio. D) Time series of the mean value ( $\pm 95 \%$ CI) of fishing mortality rate (F) predicted by the model to FMSY ratio. E) Kobe plot showing stock trajectory in relation to $F / F_{M S Y}$ and $B / B_{M S Y}$ ratios.


Figure 7. Biomass time series predicted with the CMSY method for the capelin stock in NAFO fishing areas 4R, 4S and 4T between 1975 and 2019. Upper (USR) and limit (LRP) reference points have been determined from $0.8 \times B_{M S Y}$ and $0.4 \times B_{M S Y}$, respectively.

Appendix 1. Application of the $B_{\text {msy }}$ proxy method with the time series of Greenland halibut spawning biomass estimated from the DFO scientific survey carried out in the northern Gulf of St. Lawrence from 1990 to 2019.

## Information required:

- Time series of stock biomass indices.

Approach:
Uses the mean of the stock biomass estimates during a reference period when fishing did not cause a negative effect on the population.

Indicator and/or reference point :

- Proxy of the stock biomass that produces the maximum sustainable yield ( $B_{\mathrm{MSY}}$ ).


## Assumption:

- Biomass index values are representative of the stock biomass.

Limitation and source of bias:

- Changes in natural mortality, recruitment and somatic growth in the population are not accounted for in establishing the maximum sustainable yield.

Example of results:


Figure A.1. Time series of the biomass of Greenland halibut longer than 40 cm in the bottom trawl survey conducted in the northern Gulf of St. Lawrence from 1990 to 2019 (blue line) and estimation of biomass at maximum sustainable yield proxy (BMSY, black line), from the average of the years 2004 to 2012, and identification of upper (green line) and limit (red line) reference point corresponding respectively to $80 \%$ and $40 \%$ of $B_{\text {MSY }}$.

## Information required:

- Time series of length composition in the fishery;
- Length at maturity ( $\mathrm{L}_{\mathrm{m}}$ );
- Asymptotic length ( $\mathrm{L}_{\mathrm{inf}}$ ).


## Approach :

Uses length frequencies in the fishery to estimate various indicators and compare them to reference points related to conservation, optimal yield and expected length distribution in a population at maximum sustainable yield.

## Indicators and/or reference points :

- Mean length of largest 5\% ( $L_{\text {max5 }}$ ) ;
- $95^{\text {th }}$ percentile of length distribution ( $L_{95 \%}$ );
- Proportion of individuals above $\mathrm{L}_{\text {opt }}+10 \%$ ( $P_{\text {mega }}$ );
- $25^{\text {th }}$ percentile of length distribution ( $\mathrm{L}_{25 \%}$ );
- Length at $50 \%$ of modal abundance ( $L_{c}$ );
- Mean length of individuals $>L_{c}$ ( $L_{\text {mean }}$ );
- Length class with maximum biomass in catch ( $L_{\text {maxy }}$ ).


## Assumptions:

- Recruitment, natural mortality and somatic growth are constant;
- Selectivity in the fishery follows a logistic curve;
- Length frequencies in the fishery are representative of the population.

Limitation and source of bias:

- The selectivity curve determines the individuals caught in the fishery.


## Example of results :



Figure A.2. Time series of ICES conservation indicators (top panel) and their ratio (lower panel) related to reference points based on length frequency in commercial fishery of American plaice in NAFO fishing area 4t from 1991 to 2010.
(b) Optimal Yield

(b) Optimal yield


Figure A.3. Time series of ICES optimal yield indicators (top panel) and their ratio (lower panel) related to reference points based on length frequency in commercial fishery of American plaice in NAFO fishing area 4T from 1991 to 2010.
(c) Maximum Sustainable Yield

(c) Maximum sustainable yield


Figure A.4. Time series of ICES maximum sustainable yield indicators (top panel) and their ratio (lower panel) related to reference points based on length frequency in commercial fishery of American plaice in NAFO fishing area 4T from 1991 to 2010.

Appendix 3. Application of the recent and historical trends method with time series of Greenland halibut commercial landings in NAFO fishing areas 4R, 4S and 4T, and average weight per unit effort (kg/tow) in the DFO scientific survey in the northern Gulf of St. Lawrence. Information required:

- Time series of commercial landings or abundance indices.


## Approach :

Uses a linear regression line to estimate an indicator of recent and historical trends observed in commercial fishing or scientific survey data.

Indicator and/or reference point :

- Regression coefficient value indicating the trend observed during the selected time series (increasing, stable or decreasing).


## Assumption:

- The abundance index values are proportional to the stock abundance and all individuals harvested by fishing are landed (no discard).


## Limitation and source of bias:

- There is an underestimation of the true population abundance when the quantity of discards is large and not reported.


## Example of results :



Figure A.5. Estimation of recent temporal trends (lower panels) observed from 2015 to 2019 in the values (upper panels) of Greenland halibut mean weights ( $\pm 95 \%$ IC) per unit effort in scientific surveys (left panels) and in total annual landings (right graphs).


Figure A.6. Estimation of recent temporal trends (lower panels) observed from 2010 to 2019 in the values (upper panels) of Greenland halibut mean weights ( $\pm 95 \%$ IC) per unit effort in scientific surveys (left panels) and in total annual landings (right graphs).


Figure A.7. Estimation of historical temporal trends (lower panels) observed from 1970 to 2019 in the values (upper panels) of Greenland halibut mean weights ( $\pm 95 \%$ IC) per unit effort in scientific surveys (left panels) and in total annual landings (right graphs).

Appendix 4. Application of the boosted regression tree (BRT) method with the time series of capelin commercial landings in NAFO fishing areas 4R, 4S and 4T from 1975 to 2019.

## Information required:

- Time series of commercial landings.

Approach:
Uses the reinforced regression tree learning method to parametrize a statistical model that attempts to estimate the level of stock saturation $\left(B / B_{0}\right)$ from several explanatory variables derived from commercial landing data.

Indicators and/or reference points :

- Level of stock saturation (1 - level of stock depletion);
- $B / B_{\mathrm{MSY}}$ ratio.

Assumptions:

- $B / B_{\text {MSY }}=$ saturation $\times 2$;
- Commercial landings represent the stock's level of depletion;
- Maximum catch has been reached.


## Limitation and source of bias:

- Not suitable for fisheries that are developing or showing an increasing number of commercial landings.

Example of results:


Figure A.8. Time series of the ratio of stock biomass (B) and biomass at maximum sustainable yield ( $B_{\text {MSY }}$ ) estimated with the boosted regression tree method applied to data on capelin commercial landings in NAFO fishing areas 4R, 4S and 4T from 1975 to 2019 and identification of predefined stock states (healthy, slightly overfished, overfished, severely overfished, collapsed) according to the $B / B_{\text {MSY }}$ ratio values.

Appendix 5. Application of the depletion-corrected average catch (DCAC) method with the time series of Greenland halibut commercial landings in NAFO fishing areas 4R, 4S and 4T from 1970 to 2019.

Information required:

- Time series of commercial landings;
- Natural mortality rate ( $M$ );
- $F_{\text {Msy }} / M$ ratio;
- Depletion level of the stock $\left(B / B_{0}\right)$.


## Approach :

Average commercial catch corrected by a Monte Carlo derived method that uses probability distributions of the current level of population depletion, natural mortality rate, $F_{\mathrm{MSY}} / \mathrm{M}$ and $B_{\mathrm{MSY}} / B_{0}$ ratio to estimate a distribution of maximum sustainable yield values.

## Indicator and/or reference point :

- The level of commercial catches is sustainable in the short term.

Assumptions:

- Existence of an unsustainable abnormally high quantity of catches;
- Commercial landings represent the level of depletion of the stock.


## Limitations and sources of bias:

- Suitable for species with a mortality rate equal or lower than 0.2;
- Sensitive to the assumed level of depletion of the stock;
- Estimated maximum sustainable yield values are conservative.


## Example of results :



Figure A.9. Time series of Greenland halibut commercial landings in NAFO fishing areas 4R, 4S and $4 T$ from 1970 to 2019 (solid line) and estimation of a MSY proxy (dotted line) with the depletion-corrected average catch method.

Appendix 6. Application of the optimized catch-only model (OCOM) method with the time series of Greenland halibut commercial landings in NAFO fishing areas 4R, 4S and 4T from 1970 to 2019.

Information required:

- Time series of commercial landings;
- Natural mortality rate ( $M$ ).


## Approach:

Uses a stock reduction analysis that follows a simple Graham Schaefer surplus production model to predict estimates of stock biomass and fishing mortality rates using time series of commercial landings and two parameters determined a priori, namely the population intrinsic rate of increase derived from $M$ and the stock level of depletion based on trends in the catches.

## Indicators and/or reference points :

- Maximum sustainable yield (MSY);
- Stock biomass at maximum sustainable yield (Bmsy);
- Fishing mortality rate at maximum sustainable yield ( $F_{\mathrm{MSY}}$ );
- Depletion level of the stock at the end of the catch time series.


## Assumptions:

- No migration in or out of the stock since changes in biomass result from population increase and fishing;
- The variability in the age/length distribution does not cause a delayed effect in the stock biomass dynamics;
- No change in fishing techniques (constant catchability);
- Individual growth, recruitment and mortality are combined into a single simplified production equation;
- The age and length composition in the population is stable over time;
- The catchability used to obtain a biomass index is constant over time.


## Limitations and sources of bias:

- The underestimation of FMSY values;
- The effects of variations in recruitment and mortality rates cannot be distinguished;
- Not able to detect changes in the productivity regime.

Example of results :
Table A.1. Reference points estimated from the OCOM method applied to Greenland halibut commercial landings data in NAFO fishing areas 4R, 4S and 4T between 1970 and 2019.

| Reference points | Mean | $95 \%$ Cl |
| :---: | :---: | :---: |
| $B_{\mathrm{MSY}}(\mathrm{t})$ | 23544 | $[11695 ; 63665]$ |
| $F_{\mathrm{MSY}}$ | 0.148 | $[0.031 ; 0.408]$ |


D. $\mathrm{F} / \mathrm{F}_{\mathrm{MSY}}$



Figure A.10. Graphical results obtained with the OCOM method applied to Greenland halibut commercial landings in NAFO fishing areas 4R, 4S and 4T from 1970 to 2019. A) Time series of commercial landings and mean value of maximum sustainable yield estimated ( $\pm 95 \%$ CI). B) Viable r-K pairs used to predict the stock biomass and which may explain the observed commercial landings. C) Time series of the mean value of the stock biomass predicted by the model ( $\pm 95 \%$ CI) to $B_{\text {MSY }}$ ratio. D) Time series of the mean value of the fishing mortality rate predicted by the model ( $\pm 95 \% \mathrm{Cl}$ ) to $F_{M S Y}$ ratio. E) Kobe plot showing the stock trajectory over the years in relation to $B / B_{M S Y}$ and $F / F_{M S Y}$ ratios.

## Information required:

- Time series of commercial landings;
- Time series of abundance indices from fishery or scientific surveys;
- Qualitative value of the species resilience (very low, low, medium or high);
- Population intrinsic rate of increase ( $r$ ) (optional if resilience value is known);
- Theoretical carrying capacity ( $K$ ) (optional if the resilience value is known).


## Approach :

Detects, from a Monte Carlo simulation, viable combinations of $r$ - $K$ resulting in stock biomass trajectories that could support the observed commercial landings and whose predicted values are verified by a Graham-Schaefer Bayesian state-space surplus production model.

## Indicators and/or reference points:

- Maximum sustainable yield (MSY);
- Stock biomass at maximum sustainable yield ( $B_{\mathrm{MSY}}$ );
- Fishing mortality at maximum sustainable yield ( $F_{\text {MSY }}$ );
- $B / B_{\mathrm{MSY}}$ and $F / F_{\mathrm{MSY}}$ ratios.


## Assumptions:

- The maximum of commercial landings defines the lower limit of the theoretical carrying capacity;
- The range of values used for $K$ is obtained by dividing the maximum commercial landings by the lower and upper limits of the population intrinsic rate of increase;
- No migration in or out of the stock, since the changes in the biomass result from population growth and fishing mortality;
- The variability in the age/length distribution does not cause a delayed effect in the biomass dynamics;
- No change in fishing techniques (constant catchability);
- Individual growth, recruitment and mortality are combined into a single simplified production equation;
- The age and length composition in the population is stable over time;
- The catchability used to obtain a biomass index is constant over time.


## Limitations and sources of bias:

- The MSY and $K$ values are underestimated if only commercial landings are used (without releases);
- The estimated reference points ( $B_{\text {MSY }}$ and $F_{\text {MSY }}$ ) are sensitive to the population level of depletion and intrinsic rate of increase determined a priori.

Example of results:
Table A.2. Reference points determined by the CMSY method applied to capelin commercial landings data in NAFO fishing areas 4R, 4S and 4T from 1975 to 2019.

| Reference points | Mean | $\mathbf{9 5 \% ~ C l}$ |
| :---: | :---: | :---: |
| $B_{\mathrm{MSY}}(\mathrm{t})$ | 30160 | $[24194 ; 35797]$ |
| $F_{\mathrm{MSY}}$ | 0.252 | $[0.214 ; 0.297]$ |

A. Catch
B: Viable r-K pairs
C. $\mathrm{B} / \mathrm{B}_{\text {MSY }}$




E. Kobe plot


Figure A.11. Graphical results obtained with the CMSY method applied to capelin commercial landings in NAFO fishing areas 4R, 4S and 4T from 1975 to 2019. A) Time series of commercial landings and mean value of maximum sustainable yield estimated ( $\pm 95 \%$ CI). B) Viable r-K pairs used to predict the stock biomass and which may explain the observed commercial landings. C) Time series of the mean value of the stock biomass predicted by the model ( $\pm 95 \%$ $\mathrm{Cl})$ to $B_{\text {MSY }}$ ratio. D) Time series of the mean value of the fishing mortality rate predicted by the model ( $\pm 95 \%$ CI) to $F_{\text {MSY }}$ ratio. E) Kobe plot showing the stock trajectory over the years in relation to $B / B_{M S Y}$ and $F / F_{M S Y}$ ratios.

Appendix 8. Application of the Just Another Bayesian Biomass Assessment (JABBA) method with the time series of Atlantic halibut commercial landings from 1960 to 2020 in NAFO fishing areas 4R, 4 S and 4T, as well as the time series of mean weight per unit of effort estimated from scientific surveys in the northern (1990 to 2020) and southern (1985 to 2020) Gulf of St.
Lawrence.

## Information required:

- Time series of commercial landings;
- Time series of abundance indices from fishery or scientific survey;
- Population intrinsic rate of increase ( $r$ );
- Theoretical carrying capacity ( $K$ );
- Stock level of depletion at the beginning of the time series;
- Shape of the surplus production function (Schaefer, Pella-Tomlinson or Fox).


## Approach:

Fitting a generalized state-space biomass surplus production model to obtain reproducible values of stock status determined by a Bayesian Markov chain Monte Carlo method.

## Indicators and/or reference points :

- Maximum sustainable yield (MSY);
- Stock biomass at maximum sustainable yield ( $B_{\text {MSY }}$ );
- Fishing mortality at maximum sustainable yield ( $F_{\text {MSY }}$ );
- $B / B_{\mathrm{MSY}}$ and $F / F_{\mathrm{MSY}}$ ratios.


## Assumptions:

- The stock-recruit relationship follows a Beverton-Holt function;
- There is no observation error in the commercial landings data;
- No migration in or out of the stock since the changes in the biomass result from population growth and fishing mortality;
- The variability in the age/length distribution does not cause a delayed effect in the biomass dynamics;
- No change in fishing techniques (constant catchability);
- Selectivity in fishing can take different forms as long as it remains constant over time;
- Individual growth, recruitment and mortality are combined into a single simplified production equation;
- The age and length composition in the population is stable over time;
- The catchability used to obtain a biomass index is constant over time.


## Limitations and sources of bias:

- Does not consider the annual uncertainty associated with observation errors in commercial landings data;
- Requires complete commercial landing time series without missing years.


## Example of results :

Table A.3. Stock status indicators and reference points determined with the JABBA method applied to Atlantic halibut commercial landings time series in NAFO fishing areas 4R, 4S and $4 T$, as well as time series of mean weight by unit of effort estimated from scientific surveys in the northern and southern Gulf of St. Lawrence.

| Indicators and reference <br> points | Mean | $\mathbf{9 5 \% ~ C I}$ |
| :---: | :---: | :---: |
| $B_{\mathrm{MSY}}(\mathrm{t})$ | 86472 | $[33007 ; 35797]$ |
| $F_{\mathrm{MSY}}$ | 0.038 | $[0.022 ; 0.061]$ |
| Last year $B / B_{\mathrm{MSY}}$ | 1.79 | $[0.94 ; 2.60]$ |
| Last year $F / F_{\mathrm{MSY}}$ | 0.20 | $[0.05 ; 0.55]$ |



Figure A.12. Kobe plot showing the Atlantic halibut stock trajectory in NAFO fishing areas 4R, $4 S$ and $4 T$ between 1960 and 2020 in relation to $F / F_{M S Y}$ and $B / B_{M S Y}$ ratios. The gray areas represent the $50 \%, 80 \%$ and $95 \%$ confidence intervals for the last year of the time series (2020). The probability that the terminal year point is in one of the four quadrants is indicated in the figure legend.


Figure A.13. Results of the retrospective analysis applied on the time series of the trajectory estimated by the model for A) the stock biomass, B) the fishing mortality rate, C) the $B / B_{M S Y}$ ratio, D) the $F / F_{\text {Msy }}$ ratio, E) the $B / B_{0}$ ratio and F) the function describing the surplus production in relation to the stock biomass. The areas in gray represent the 95\% confidence intervals. The black line represents the reference model including all the years and each coloured line that follows represents the withdrawal of one year each time to fit the JABBA model again.

Appendix 9. Application of the stochastic surplus production model in continuous time (SPiCT) method with the time series of Greenland halibut commercial landings in NAFO fishing areas $4 R, 4 S$ and $4 T$ and to the stock biomass indices estimated from scientific surveys in northern Gulf of St. Lawrence between 1990 and 2019.

## Information required

- Time series of commercial landings;
- Time series of abundance indices from fishery or scientific surveys (optional).


## Approach :

Fitting a state-space Pella-Tomlinson biomass surplus production model that incorporates observation errors in commercial landings and abundance indices, as well as process errors associated with fishing and changes in population size.

## Indicators and/or reference points :

- Maximum sustainable yield (MSY);
- Stock biomass at maximum sustainable yield ( $B_{\mathrm{MSY}}$ );
- Fishing mortality at maximum sustainable yield ( $F_{\text {MSY }}$ );
- $B / B_{\mathrm{MSY}}$ and $F / F_{\mathrm{MSY}}$ ratios.


## Assumptions:

- No migration in or out of the stock since the changes in the biomass result from population growth and fishing mortality;
- The variability in the age/length distribution does not cause a delayed effect in the biomass dynamics;
- Individual growth, recruitment and mortality are combined into a single simplified production equation;
- No change in fishing techniques (constant catchability);
- Selectivity in fishing can take different forms as long as it remains constant over time;
- The age and length composition in the population is stable over time;
- The catchability used to obtain a biomass index is constant over time.


## Limitations and sources of bias:

- The performance of the model is better in the presence of significant contrasts in the effort, biomass and exploitation rate data;
- It is preferable to reduce the number of parameters considered in the model when the time series are short or there is little contrast in the data.


## Example of results :



Figure A.14. Graphical results obtained with the SPiCT model applied to the Greenland halibut commercial landings in NAFO fishing areas 4R, 4S and 4T and to stock biomass indices estimated from scientific surveys in northern Gulf of St. Lawrence making it possible to visualize time series of A) the stock biomass predicted by the model ( $\pm 95 \%$ CI), B) the absolute fishing mortality rate ( $\pm 95 \%$ CI), C) the commercial landings, D) the B/BMS ratio ( $\pm 95 \%$ CI), E) the $F / F_{\text {MSY }}$ ratio ( $\pm 95 \%$ CI). The graphical results also include F) a Kobe plot showing the stock trajectory from 1990 to 2019 in relation to the $F / F_{M S Y}$ and $B / B_{M S Y}$ ratios, G) the function describing the surplus production curve as a function of the stock biomass $(B / K), H)$ the time required to reach the $B_{M S Y}$ value under different fishing mortality rates and I) the prior and posterior probability distributions for the parameter that describes the intrinsic rate of population increase.


Figure A.15. Results of the retrospective analysis for A) the stock biomass, B) the fishing mortality rate, C) the $B / B_{M S y}$ ratio and D) the F/FMSy ratio. The areas in gray represent the $95 \%$ confidence intervals. The black line represents the reference model including all the years and each coloured line represents the additional removal of one year to refit the SPiCT model. Mohn's mean value is used to check whether the predicted trajectories show retrospective patterns.

Appendix 10. Application of the mean length total mortality estimator (MLZ) method with the time series of American plaice lengths in commercial catches in the NAFO fishing area 4T from 1991 to 2006.

Information required:

- Time series of lengths in commercial catches;
- Asymptotic length ( $L_{i n t}$ );
- The von Bertalanffy growth coefficient (k).


## Approach:

Uses the lengths in the fishery to predict a mean length time series with a nonequilibrium Berverton-Holt equation. Then, the year and the total mortality values ( $Z$ ) that make the mean lengths best fit the lengths in the fishery are estimated with a maximum likelihood approach.

## Indicator and/or reference point :

- Instantaneous total mortality rate (Z).


## Assumptions:

- The population is not at equilibrium;
- Recruitment is constant over time or variation over time are small and without trends;
- Growth is deterministic, follows a von Bertalanffy growth equation, and is time invariant;
- Knife-edge selectivity curve above the length of full selectivity;
- Selectivity is time invariant;
- All individuals that are longer than the length at full selectivity are caught in the fishery.


## Limitations and sources of bias:

- The effects of variations in recruitment and in the mortality rate are indistinguishable.;
- Not appropriate if the selectivity in fishing varies over time;
- Not suitable for organisms with a short life expectancy.

Example of results :


Figure A.16. Time series of relative length frequencies of American plaice sampled in NAFO fishing area $4 T$ between 1991 and 2006. The vertical red line represents the length at which individuals are fully selected in the fishery ( 35 cm ).

Table A.4. Variations in the total instantaneous mortality rate ( $Z$ ) with different numbers of significant changes (inflection points) in total mortality estimated from the length composition of American plaice caught in the NAFO fishing area 4T between 1991 and 2006.

| Number of <br> inflection points | Time <br> series | Z estimate | Standard error |
| :---: | :---: | :---: | :---: |
| 0 | $1991-2006$ | 0.432 | 0.020 |
| 1 | $1991-1994$ | 0.391 | 0.028 |
|  | $1994-2006$ | 0.477 | 0.036 |
| 2 | $1991-1996$ | 0.381 | 0.021 |
|  | $1996-1997$ | 1.203 | 1.463 |
|  | $1997-2006$ | 0.421 | 0.044 |



Figure A.17. Time series of American plaice mean length in NAFO fishing area 4T between 1991 and 2006 that are greater than the length at full selectivity ( 35 cm ). The solid lines represent the mean length values predicted by an nonequilibrium Beverton-Holt equation that correspond most closely to the length time series observed in the fishery and to the total mortality rate with none (blue), 1 (red) or 2 (turquoise) inflection points of changes in mortality values.

Appendix 11. Application of the length-based spawning potential ratio (LB-SPR) method with the time series of American plaice lengths in commercial catches in the NAFO fishing area 4T from 1991 to 2000.

Information required:

- Time series of lengths in commercial catches;
- Asymptotic length ( $\mathrm{L}_{\mathrm{inf}}$ );
- Linf coefficient of variation (CV);
- Rate of natural mortality to von Bertalanffy growth coefficient ratio (M/k);
- Length at $50 \%$ ( $L_{m 50}$ ) and 95\% ( $L_{\text {m95 }}$ ) maturity;
- Length at first catch $\left(\mathrm{L}_{\mathrm{c}}\right)$.


## Approach:

First, use the length data in the portion of the frequency curve above the length at $50 \%$ maturity to estimate the corresponding egg production by transforming the lengths into fecundity values. Then compare the egg production for different levels of fishing mortality with that obtained in the absence of fishing.

## Indicators and/or reference points :

- Ratio of the fishing mortality rate to natural mortality rate ( $F / M$ );
- Selectivity at age in the fishery;
- Spawning potential ratio.


## Assumptions:

- The population is at equilibrium;
- Recruitment, natural mortality and individual growth are constant;
- Lengths in the fishery are representative of the population;
- Maturity and selectivity in the fishery are described by a knife-edge distribution towards the length at maturity and the length at full selectivity, respectively.


## Limitations and sources of bias:

- The results obtained considering a population at equilibrium do not necessarily represent reality, given the stochastic components of the environment;
- There is uncertainty if selectivity in the fishery is not asymptotic;
- Provides imprecise estimates when the length frequencies have multiple modes.

Example of results:


Figure A.18. Time series of estimated values for selectivity, F/M ratio and spawning potential ratio with the LB-SPR method applied to American plaice length data in the fishery from NAFO fishing area 4 T between 1991 and 2000. The points represent the mean values ( $\pm 95 \% \mathrm{Cl}$ ) of the selectivity, the F/M ratio and the spawning potential ratio values estimated from length data in the fishery. The lines represent the values for these three variables predicted with the model employed by the LB-SPR method.

Appendix 12. Application of the length-based integrated mixed effects (LIME) method with the time series of American plaice lengths in commercial catches in the NAFO fishing area 4T from 1993 to 2006.

## Information required:

- One or multiple years of lengths in commercial catches;
- Length-weight relationship;
- Natural mortality;
- Length at 50\% maturity;
- Time series of commercial landings (optional);
- Time series of abundance indices from fishery or scientific surveys (optional).


## Approach:

Use an age-structured population dynamics mixed-effect model to estimate random variation in recruitment, fishing mortality, and observation error in length sampling, as well as the magnitude of random variation of these different processes.

## Indicators and/or reference points :

- Annual fishing mortality rate ( $F$ );
- Length at $50 \%$ and $95 \%$ of selectivity in the fishery;
- Spawning potential ratio;
- Stock biomass at maximum sustainable yield ( $B_{\text {MSY }}$ );
- Fishing mortality rate at maximum sustainable yield.


## Assumptions:

- The population is not at equilibrium;
- Annual recruitment is treated as a random effect in the model;
- Lengths in the fishery are representative of the population.


## Limitations and sources of bias:

- Inappropriate if only one year of length data is used to assess a species with long life expectancy;
- Model performance is increased for short and medium-lived species when at least 10 years of length data are available.


Figure A.19. Time series of mean values (solid line) and 95\% Cls (pale green area) estimated with the LIME method applied to American plaice fishery length data in the NAFO fishing area $4 T$ between 1993 and 2006 for $A$ ) the fishing mortality rate, B) the recruitment, $C$ ) the spawning potential ratio (SPR), D) the mean length and E) the relative spawning stock biomass. The dotted and dashed lines in figures A and C represent respectively the upper and limit reference points. F) Selectivity at length resulting from parameters set a priori (length at 50\% and 95\% selectivity in the fishery) used to parametrize the model employed by the LIME method.

Appendix 13. Application of the length-based Bayesian biomass estimation (LBB) method with the time series of American plaice lengths in commercial catches in the NAFO fishing area 4T from 1991 to 2006.

Information required:

- Time series of lengths in commercial catches;
- Asymptotic length ( $\mathrm{L}_{\text {int }}$ );
- Length at 50\% maturity;
- Rate of natural mortality to von Bertalanffy growth coefficient ratio (M/k).


## Approach :

Uses a Bayesian Markov chain Monte Carlo method to derive probability distributions for the Linf, the $M / k$, the $F / k$ and the length at first capture parameters that are used to fit a simplified biomass dynamics equation.

## Indicators and/or reference points :

- Length at first capture ( $\mathrm{L}_{\mathrm{c}}$ );
- Length at first capture that generates the maximum sustainable yield ( $\mathrm{L}_{\mathrm{c} \_ \text {opt }}$ );
- Relative rate of natural mortality and fishing mortality;
- $B / B_{0}$ and $B / B_{\text {MSY }}$ ratio;
- Yield per recruit.


## Assumptions:

- Growth in length is obtained from the von Bertalanffy growth equation with a Beverton-Holt shape;
- The population is at equilibrium;
- Mortality, growth and recruitment in the population vary around the mean values in the different age classes;
- The lengths in the fishery are representative of the population.


## Limitations and sources of bias:

- Inappropriate if inter-annual variability in recruitment is high;
- Inappropriate if the different fishing equipment used has variable selectivity.


Figure A.20. Graphical results obtained following the application of the LBB method to American plaice fishery length data in NAFO fishing area $4 T$ between 1991 ad 2006. A) Cumulative length data (LF) used to estimate the values a priori for parameters $L_{c}, L_{\text {inf }}$ and $Z / k$. B) LF data available for the first (1991) and C) the last year (2006) of the time series. The red line in these two graphs represents the fitting curve of the equation used to estimate $Z / k, M / k, F / k, L_{c}$ and $L_{\text {inf. }}$. $L_{\text {opt }}$ is calculated from $L_{\text {inf }}$ and $M / k$ and represent a reference point. D) Time series of mean length values ( $L_{\text {mean }}$ ) in relation to $L_{\text {opt }}$ and $L_{c}$ reference points (dotted black curve). E) Time series of relative rate of fishing mortality F/M (solid curve) and 95\% confidence intervals (dashed curves) in relation to the reference point where fishing mortality equals natural mortality ( $F=M$ ). F) Time series of relative biomass $B / B_{0}$ (solid curve) in relation to reference points which represent a proxy of $B_{M S Y}$ (dotted green line) and $0.5 \times B_{\text {MSY }}$ (dotted red line).

