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Ecosystems and  
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## **Canadian Science Advisory Secretariat (CSAS)**

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**Research Document 2026/011**

**Quebec Region**

### **Identification of a Limit Reference Point for Iceland Scallop in Area 16E**

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## Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

### Published by:

Fisheries and Oceans Canada  
Canadian Science Advisory Secretariat  
200 Kent Street  
Ottawa ON K1A 0E6

[http://www.dfo-mpo.gc.ca/csas-sccs/  
DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca](http://www.dfo-mpo.gc.ca/csas-sccs/DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca)



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ISSN 1919-5044

ISBN 978-0-660-97774-4 Cat. No. Fs70-5/2026-011E-PDF

### Correct citation for this publication:

Belley, R., Sean, A.-S., and Bermingham, T. 2026. Identification of a Limit Reference Point for Iceland Scallop in Area 16E. DFO Can. Sci. Advis. Sec. Res. Doc. 2026/011. vii + 27 p.

### ***Aussi disponible en français :***

*Belley, R., Sean, A.-S. et Bermingham, T. 2026. Détermination d'un point de référence limite pour le pétoncle d'Islande de la zone 16E. Secr. can. des avis sci. du MPO. Doc. de rech. 2026/011. vii + 29 p.*

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## ABSTRACT

Fisheries and Oceans Canada (DFO) conducts a review and assessment of scallop stocks in Quebec coastal waters every three years. The most recent review was held on March 8–9, 2023, at the Maurice Lamontagne Institute (MLI) in Mont-Joli, Quebec.

As part of this review and the development of a precautionary approach for Iceland scallop in Area 16E on Quebec’s North Shore, a Bayesian state-space surplus production model was fit to commercial landings and biomass index data from research surveys on the stock.

This document describes the method used to fit the Bayesian state-space surplus production model to biomass data for Iceland scallops in Area 16E. The results indicate that the model can be used to accurately estimate Iceland scallop biomass, assess stock status and determine a limit reference point (LRP) for this stock. The results are consistent with previous stock assessments and indicate that the stock in this area has been declining for a number of years, with stock biomass reaching its lowest recorded level in 2022 since fishing data first became available in 1987. In 2022, the LRP was set at 40% of the theoretical biomass at maximum sustainable yield ( $B_{MSY}$ ), or 182.8 tonnes (t). The stock has been in the critical zone of the precautionary approach since 2008.

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## INTRODUCTION

Quebec has two native scallop species: the sea scallop (*Placopecten magellanicus*) and Iceland scallop (*Chlamys islandica*) (Figure 1). These species primarily inhabit substrates composed of gravel, shell or rock, typically at depths ranging from 20 to 60 metres (m). They are unevenly distributed across the Estuary and Gulf of St. Lawrence (Figure 2). The Iceland scallop is predominant in the Estuary and along the North Shore (including Area 16E, which is the focus of this document), as well as around Anticosti Island. It is also found, though in lower abundance, along the southern slope of the Laurentian Channel. In contrast, the sea scallop is the dominant species in the southern Gulf, particularly along the Gaspé Peninsula, in Chaleur Bay and around the Magdalen Islands, with lower concentrations sometimes occurring in the bays of the Lower North Shore. Although scallops are capable of moving to evade predators, they are sedentary species that occur in aggregations called “beds.” This characteristic is important to consider when developing conservation strategies and fishing plans, as it raises concerns about local and serial depletion (Smith 2003).

Growth in length occurs at a slower rate in the Iceland scallop than in the sea scallop (Giguère *et al.* 2000). Growth rates vary by area and are influenced by habitat quality and environmental conditions. In the Gulf of St. Lawrence, Iceland scallops reach commercial size (70 mm) at approximately eight years of age, while sea scallops attain commercial size (100 mm) in about six years.

Scallops are dioecious, with separate sexes, and eggs are fertilized externally. Egg production is proportional to the cube of the scallop’s size, and successful fertilization depends on the density and proximity of other individuals, among other things. The spawning period is brief and does not occur simultaneously across the Gulf. Iceland scallops spawn between mid-July and late August along the North Shore and around Anticosti Island (Barber and Blake 1991; Giguère *et al.* 1994). Sea scallops spawn in August in Chaleur Bay, while spawning in the Magdalen Islands begins in late August (Giguère *et al.* 1994).

Larval development in scallops spans approximately five weeks, from egg fertilization to metamorphosis (Giguère *et al.* 1995). During this period, larvae are dispersed in the water column. Following metamorphosis, individuals settle on the seabed and adopt a benthic lifestyle. Juvenile scallops typically settle near adults. Scallop beds are usually located in areas favourable to larval retention; however, the presence of suitable substrate is critical for successful juvenile settlement. Juvenile Iceland scallops are frequently observed attached to the interior surfaces of the shells of dead adults (R. Belley, DFO, unpublished data). During the settlement phase, juveniles are highly sensitive to sediment disturbance caused by fishing gear. To ensure better juvenile survival rates during settlement, it is recommended that scallop beds not be dredged between August and November.

Both scallop species are commercially harvested. In Area 16E, along the North Shore, landings are believed to consist predominantly of Iceland scallops, which are the dominant species in this region. Landings typically consist of the adductor muscle only. Scallop landings in Area 16E were high in the past, peaking at 132 t in 1991, but have declined steadily since then, falling below 16 t annually since 2013 (DFO 2023). In 2020, 2021 and 2022, annual landings in this area totalled 14.1, 9.2 and 10.6 t of meat, respectively. Fishing effort has also decreased, from over 200 days at sea prior to 2008 to an average of 43 days during the 2020–2022 period (out of the total 79 fishing days allowed in 2022). The decline in landings in this fishing area is likely attributable to removal rates exceeding what the stock can withstand, as well as to various socio-economic factors.

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The scallop stock in Area 16E was identified as a priority for a rebuilding plan in response to Recommendation 2.63 from the Commissioner of the Environment and Sustainable Development, as outlined in the 2016 audit report entitled “Sustaining Canada’s Major Fish Stocks—Fisheries and Oceans Canada.” The Area 16E stock is also included in the second batch of stocks being proposed for the Fish Stocks provisions of the *Fisheries Act*. Under these provisions, DFO is required to maintain major fish stocks at levels necessary to promote sustainability of the stock and to develop and implement rebuilding plans for stocks that have declined below their limit reference point (LRP). At the request of the Fisheries Management Branch, a new stock assessment model and LRP for the Iceland scallop stock in Area 16E have been developed and are described in this document.

Until now, no population assessment model was available that could estimate trends in population abundance and fishing pressure for this stock. To establish an LRP, a new assessment model has been proposed to

1. estimate the population biomass in the fished beds covered in the research survey;
2. determine an LRP consistent with the precautionary approach;
3. estimate the removal rate; and
4. enable projections (not included in this document).

This document presents the results of fitting a Bayesian state-space surplus production model (SPM) to the biomass data for the Iceland scallop stock in Area 16E. This model was presented at the peer review and used to establish an LRP (DFO 2023). It uses commercial landings data and four indices of population size derived from the research survey. This type of model (SPM) is routinely used in stock assessments, notably for northern shrimp stocks in the Gulf of St. Lawrence (Smith and Bourdages 2024) and sea scallop stocks in Nova Scotia (Smith and Hubley 2014). More recently, Harbicht *et al.* (2024) evaluated nine data-limited methods for assessing the sea scallop stock in the southern Gulf of St. Lawrence and concluded that the Bayesian state-space model (like the one described here) is the most suitable based on its characteristics, assumptions and estimates.

The model fitting results can be used to estimate several biological parameters that describe the dynamics of these stocks. To assess the stability of the model in relation to our assumptions and the different sources of uncertainty, we examined several versions of this model in order to determine a model formulation that was the most suitable in the context of the assessment of the status of the Iceland scallop stock in Area 16E. The results obtained can be used in the development of the precautionary approach.

## METHODS

### DATA USED

Fitting an SPM requires a time series of total catch (landings) data and one or more time series of biomass index values representing the exploitable component of the stock. The annual landings data used go back to 1987 (Table 1, Figure 3). Estimates of the biomass of Iceland scallops measuring 70 mm and larger (minimum commercial size) derived from the DFO research survey, typically conducted every two years in May and June since 1990 (Figure 4), were used to represent the exploitable components of the stock. Incorporating fishery independent data in the model helps to mitigate the issue of hyperstability that can occur when the catch per unit effort (CPUE) from the commercial fishery is used (Shumway and Parsons 2016). The DFO research survey employs a lined Digby scallop dredge, and biomass

estimates for each sampled station are calculated in grams per square metre (g/m<sup>2</sup>). A detailed description of these data and the methods used to acquire and process them is provided in Trottier *et al.* (2017). Subsequently, to refine the dataset, only beds (i.e., areas where scallop populations naturally aggregate) with at least one recorded fishing activity between 1999 and 2019, based on logbook position data, were retained (Figure 5). Stations located in beds A, C, D, F, H, R and Q were included (Figures 4 and 5 and Table 2). In addition, stations removed from the research survey in 2005 owing to low scallop abundance were excluded from the analysis. Ultimately, four biomass indices were used, representing average biomass at their respective stations: (1) normal index (N: 38 stations sampled since 1990); (2) S2003 index (14 stations added in 2003); (3) S2004 index (8 stations added in 2004); and (4) S2007 index (6 stations added in 2007). Stations F15 and F16 were added to the research survey in 2001, but were included in the S2003 index owing to their limited number. The 1991 data from the stations in the N group and the 2019 data from stations in the S2007 group were excluded owing to the abnormally low biomass observed compared with that in the preceding and subsequent years (Table 1). In the second case (2019 data from the S2007 group), it was determined that the low biomass values were likely caused by the reduced efficiency of the gear during adverse weather conditions (high waves) when the stations were sampled. The reason for the low biomass values obtained in 1991 remains unknown.

## SURPLUS PRODUCTION MODEL

The surplus production model is based on the logistic growth of a discrete population (Verhulst 1838). Recruitment, growth and mortality are pooled together to describe the productivity of a population in its environment, as well as trends in its biomass. The model assumes that a population is productive enough to persist over time by producing more recruits than the environment has the capacity to support. The maximum sustainable yield (MSY) is the average maximum amount of biomass that can continually be removed from a fishery stock under existing environmental conditions. However, it is recognized that this theoretical value should be considered a limit and not a target (Pauly and Froese 2021).

The Schaefer-type surplus production model (SPM) (Schaefer 1954) was formulated in a Bayesian state-space framework (Meyer and Millar 1999). State-space models make it possible to estimate process error, which is related to population dynamics, as well as observation error, which is associated with the biomass index. This approach is considered by many to be a best practice in stock assessment (Aeberherd *et al.* 2018; Punt 2023).

The stochastic form of the process equation is:

$$P_t = (P_{t-1} + rP_{t-1}(1 - P_{t-1}) - \frac{C_{t-1}}{K})e^{\eta_t}$$

where  $r$  is the intrinsic rate of population increase, which encompasses all growth, recruitment and natural mortality processes;  $K$  is the carrying capacity of the system;  $C_t$  is the sum of catches in year  $t$  estimated from the observed values using a log-normal distribution with a coefficient of variation (CV) of 0.1;  $P_t$  is the ratio of exploitable biomass ( $B_t$ ) in year  $t$  to carrying capacity ( $P_t = B_t/K$ ); and  $\eta_t$  is the process error  $\eta_t \sim N(0, \sigma_{\eta}^2)$  with process variance  $\sigma_{\eta}^2$ . The model estimates biomass as a proportion of carrying capacity in order to improve the sampling of parameter space and minimize autocorrelation between each state and  $K$  (Meyer and Millar 1999). This also ensures that process error and observation error are treated separately from the uncertainty in the estimates of  $r$  and  $K$  (Froese *et al.* 2017; Pedersen and Berg 2017; Winker *et al.* 2018).

An observation equation is used to link biomass ( $B_t$ ) and the observations from the lined Digby dredge survey:

$$I_t = (qB_t)e^{\varepsilon t}$$

where  $I_t$  is the biomass index in year  $t$ ;  $q$  is the catchability coefficient; and  $\varepsilon t$  is the observation error associated with the biomass index  $\varepsilon t \sim N(0, \sigma_{\varepsilon, t}^2)$  with variance  $\sigma_{\varepsilon, t}^2$  which is composed of a minimum variance, fixed at  $0.2^2 \sigma_{fix}^2$  (Winker *et al.* 2018; Smith et Bourdages 2024), and an estimated portion  $\sigma_{est, t}^2$ .

The Bayesian SPM approach makes it possible to determine the probability distribution (posterior distributions, or “posteriors”) of the different possible values of the parameters estimated by the model. Known or estimated information on these parameters (prior distributions, or “priors”), the observed data, and the likelihood function are used to generate the posterior distributions. This approach allows uncertainty to be included and propagated to the observations, as well as to the biomass trends and the productivity of a stock when its status is being assessed (Winker *et al.* 2018).

The biomass trajectories were calculated using prior estimates for  $K$ ,  $r$ ,  $q$  and biomass as a proportion of  $K$  in the first year of the time series of catches ( $B_1/K$ ), as well as process error variance and observation error variance,  $\sigma_{\varepsilon, t}^2$  and  $\sigma_{est, t}^2$  respectively. The parameters estimated by the SPM are as follows:  $r$ ,  $K$ ,  $q$ ,  $B_1/K$ ,  $\sigma_{\eta}^2$ ,  $\sigma_{est, t}^2$ ,  $C_t$  and  $P_t$  (Smith and Bourdages 2024).

The model allows annual biomass ( $B_t$ ) and the annual exploitation rate ( $F_t$ ) to be calculated, along with reference points based on the MSY: the exploitation rate that would maintain the MSY ( $F_{MSY}$ ), biomass at MSY ( $B_{MSY}$ ), and the ratios  $B_t/B_{MSY}$  and  $F_t/F_{MSY}$ . These values are calculated using the following equations:

$$B_{MSY} = \frac{K}{2}$$

$$F_{MSY} = \frac{r}{2}$$

$$MSY = F_{MSY} \times B_{MSY} = \frac{rK}{4}$$

$$B_t = KP_t$$

$$F_t = \frac{C_t}{B_t}$$

Model fitting is performed using an extension of the stock assessment platform JABBA (“Just Another Bayesian Biomass Assessment”; Winker *et al.* 2018, 2020). JABBA enables the user to prepare data to be used to fit a generalized Bayesian state-space SPM, format model outputs, conduct diagnostic tests and generate plots.

Overall, JABBA prepares the input to be processed with the JAGS (“Just Another Gibbs Sampler”; Plummer 2003) software, which is written in C++. JAGS uses Markov Chain Monte Carlo (MCMC) simulations to make Bayesian inferences, which then allows JABBA to compile the model using code generated by R2jags (Su and Yajima 2012). All code used to perform the analyses and generate the plots was written in R (R Core Team 2024; version 4.2.2).

MCMC sampling of the posterior distributions of the parameters was carried out using 2 chains, 30,000 iterations and an adaptation period of 5,000 iterations. Samples were thinned to every fifth iteration to reduce the possibility of autocorrelation within the series. Therefore, the final number of samples in each posterior distribution was  $(30,000 - 5,000)/5 \times 2$  chains, or 10,000 samples per parameter.

---

## PRIOR DISTRIBUTION

In Bayesian modelling, prior distributions, or priors, are provided for each parameter in the model. The data and the likelihood function (Winker *et al.* 2018) are used to generate the posterior distributions. This differs from frequentist modelling approaches in that the likelihood values are weighted by the priors to provide the posteriors. One of the advantages of this probabilistic methodology is that it allows prior knowledge to be used when the required information is unavailable or uncertain.

Priors can be based on knowledge acquired in previous studies, research on different stocks of the same species or similar species, relationships based on ecological laws and theories, and expert opinion (Krushke 2021, Pauly and Froese 2021, Smith and Bourdages 2024). JABBA allows the user to select the form and scale for certain parameters (Table 3). When prior knowledge is limited, a uniform prior distribution was used, generally considered to be non-informative except for the bounds, while other informative distributions (log-normal and inverse gamma) were used when the information was deemed sufficient to guide the fitting process.

## INTRINSIC RATE OF INCREASE ( $r$ )

The priors for  $r$  for the stock have a uniform distribution, with a range of minimum and maximum values between 0.05 and 0.3. These values were chosen to represent a broad enough range of plausible values for this species, which is characterized by low resilience and productivity, according to the SeaLifeBase website (Palomares *et al.* 2023). The input intervals are then converted to log-normal priors, which are considered to provide better convergence properties than uniform priors.

## CARRYING CAPACITY ( $K$ )

The prior distribution for  $K$  also has a uniform distribution, with minimum and maximum values ranging from 500 to 1,000 t for the stock. This distribution was established by using information from the time series of catches as well as our knowledge of the species' productivity ( $r$ ). We assumed that

1. the  $K$  for the stock should be greater than the maximum catch in the respective time series; and
2. catches account for a larger proportion of  $K$  in strongly depleted stocks than in healthy stocks (Froese *et al.* 2017).

We therefore chose a range of values corresponding to approximately four to eight times the highest catch value observed for the stock. The default prior distribution for  $K$  in JABBA is eight times the maximum catch with a standard deviation of approximately 0.83 (CV = 1). These ranges of values are transformed by JABBA into log-normal distributions. JABBA penalizes the likelihood of values of  $K < 0.01$  and  $K > 10^{10}$  by default.

## CATCHABILITY COEFFICIENT OF THE BIOMASS INDEX ( $q$ )

Although a total biomass index is used, we chose a non-informative distribution for  $q$  based on the recommendations of Punt and Hilborn (1997). The default in JABBA is a uniform distribution, that is, a range from  $10^{-30}$  to 1,000. JABBA penalizes the likelihood of values diverging from these bounds, by default.

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## INITIAL DEPLETION IN THE FIRST YEAR OF THE SERIES ( $B_1/K$ )

We followed the recommendations of the ICES WKLIFE IV and V working groups (ICES 2015) and those of Froese *et al.* (2017) that  $B_1/K$  should be specified by taking into account the stock's exploitation history and its assumed level of depletion. Although exploitation was relatively lower prior to 1987, three decades of fishing on the North Shore suggest that the Iceland scallop stock was likely at an average level relative to the area's carrying capacity in 1987. We therefore determined that the  $B_1/K$  for the stock could be described by a log-normal distribution with a mean value of 0.5 and a CV of 0.5. We assume, with this distribution, that biomass values were average relative to carrying capacity in 1987.

## PROCESS AND OBSERVATION ERROR VARIANCE

We used JABBA's default option for the process error and observation error variance parameters, i.e., a  $1/\text{gamma}(4, 0.01)$  distribution. This corresponds to an average process error of 0.059, with 95% confidence intervals of approximately 0.03 to 0.1, and a CV of 28% (Winker *et al.* 2018). This level of process error is consistent with the values at which state-space SPM models are most likely to perform adequately (Thorson *et al.* 2014). A minimum variance of 0.2 was set for  $\sigma_{\text{fix}}$ , following the recommendations from the JABBA authors on plausible observation error values and the partitioning of observation error with process error (Winker *et al.* 2018). Annual catches are assumed to be accurate as reported, given the relatively robust catch monitoring system for scallops.

## DIAGNOSTICS

Model fit was assessed in each case by means of several statistics and plots calculated and generated automatically by JABBA (Carvalho *et al.* 2021; Winker *et al.* 2018). The log-normal residuals of the observed and predicted biomass index values were first inspected visually to check for problematic temporal trends. The root mean square error (RMSE), standard deviation of the normalized residuals (SDNR) and the deviance information criterion (DIC) were also calculated.

The quality of the posterior distributions of certain key parameters as well as the influence of the data in relation to the priors on the posterior distributions was evaluated using the prior posterior mean ratio and the prior posterior variance ratio (PPMR and PPVR respectively).

The stability of the estimates and the model's consistency in relation to our assumptions as well as its capacity to simulate and predict values similar to our observations were also evaluated. We began by examining the process error deviation. We ensured that the simulated values of the posterior predictive distribution could reproduce biomass values that included our observations (posterior predictive check, or PPC).

Finally, we performed retrospective analyses spanning five years to see whether the estimates would remain stable after more information was added. We inspected the plots for evidence of extreme bias and confirmed that the estimates remained within the confidence intervals of the full model. Mohn's rho statistic was also used to measure the severity of retrospective patterns (Mohn 1999; Punt 2023).

## SENSITIVITY ANALYSIS

A crucial step in Bayesian modelling is assessing the stability in parameter estimation in relation to the inherent uncertainty in our assumptions (Punt 2023). We therefore compared the results obtained from our base model using a series of sensitivity tests (figures 13 and 14).

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Since the system's carrying capacity was unknown, we varied the means of the prior distributions of  $K$ . We analyzed scenarios using priors for  $K$  with different bounds: less informative (200–1,500 t), lower (200–700 t) and higher (800–1,500 t).

It is recognized that the value of the initial relative biomass ( $B_1/K$ ) can have a considerable effect on the results of several stock assessment methods (Boudreau and Duplisea 2022) and can lead to biased advice if the model is not suitable for describing the dynamics of the system. We therefore developed scenarios with low (mean of 0.2 and CV of 0.5) and high (mean of 0.8 and CV of 0.5) values for  $B_1/K$ .

For these sensitivity tests, we visually compared the model estimates against those of the base model to ensure that the results were consistent.

The Bayesian surplus production model (SPM) was fit to the data for the Area 16E Iceland scallop stock. Posterior distributions for the stock are presented in tables 4 and 5 and Figure 6. The parameter estimates for  $r$ ,  $K$ ,  $B_1/K$  and  $q$  are plausible given the ecology of the Iceland scallop, as well as the sampling plan for the research survey (using a lined Digby dredge), on which the values for calculating the biomass indices are based. Furthermore, the levels of annual process and observation variance for the stock are reasonable and fall within the range of values where SPMs perform adequately (Thorson *et al.* 2014; Winker *et al.* 2018). The observed data also fall within the posterior and posterior predictive distributions (Figure 7). Furthermore, for  $r$ ,  $K$  and  $B_1/K$ , the PPMR values indicate that the means of the distributions were updated by the model and increased relative to the prior values, while the PPVR values were less than 1, indicating that the data informed the model and reduced the uncertainty in these three parameters.

## MODEL FITTING

The observed values for the annual biomass index fall within the posterior distribution and the posterior predictive distribution (Figure 7). The analysis of residuals shows a slight tendency to underestimate biomass at the beginning of the time series (1990) of the normal (N) index. Overall, the model's fit to the stock data is considered acceptable (RMSE = 30.1; SDNR = 1.31) (Figure 8).

The absolute and relative trends in biomass at MSY and the stock exploitation rate are shown in Figure 9. A relatively steady decline in biomass can be observed from the beginning of the time series until 2022, while fishing mortality generally exceeded the level of recruitment in the stock according to the model. The results of the retrospective analyses demonstrated that adding an additional year of data did not significantly affect biomass estimates for the subsequent year, suggesting that the model's parameter estimates are relatively stable and appropriate. Model estimates fall within the model's confidence intervals and show no systematic bias toward underestimation or overestimation (Figure 10). The process error deviation (Figure 11) remains close to zero over the time series, fluctuating between slightly positive or negative values without any clear trend. In 2022, the stock biomass would be below the  $B_{MSY}$  and above the  $F_{MSY}$  according to the model (figures 9 and 12).

## SENSITIVITY ANALYSIS

We carried out sensitivity analyses of the prior values to test our assumptions on carrying capacity ( $K$ ) and the initial biomass depletion rate ( $psi$  or  $B_1/K$ ). The objective was to determine whether the base model is sensitive to values that differ from (and are considered less likely than) our assumptions of the prior values in the base model. Changes in our underlying assumptions did not yield results that differed appreciably from those obtained from our base model, given that the sensitivity analyses produced parameter estimates that are similar to

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those of the base model. Visual inspection of the biomass trajectories calculated using these models showed that they all fall within the confidence intervals for the base model and exhibit the same trends (figures 13–14).

## LIMIT REFERENCE POINT AND STOCK STATUS

The estimated stock biomass has declined steadily since the beginning of the time series of fishing data, reaching a record low of 99.69 t in 2022 (Table 6). In 2022, a limit reference point (LRP) of 40% of the theoretical biomass at maximum sustainable yield ( $B_{MSY}$ ) was established, equivalent to 182.8 t (Figure 9). The stock has remained in the critical zone of the precautionary approach framework since 2008. The exploitation rate estimated by the model indicates that fishing effort has likely exceeded the level the stock could sustain since 1990, except in 2010 and 2014 (Figure 12). Since the stock is in the critical zone, a rebuilding plan is scheduled for Area 16E in the coming years.

## SOURCES OF UNCERTAINTY

A surplus production model was used to describe the trajectory of Iceland scallop stocks in Area 16E over time. This model does not integrate information on the size or age structure of the population, and simplifies productivity processes (recruitment, growth, natural mortality, etc.) by limiting them to two parameters:  $r$  (population growth rate) and  $K$  (environmental carrying capacity). Essentially, next year's biomass is equal to this year's biomass, plus stock productivity, and minus fishery catches.

There is no information available to confirm whether Iceland scallop productivity in Area 16E has changed significantly in recent years. These changes are only partially captured by the model's process error. Consequently, the SPM can be used heuristically to estimate biomass at maximum sustainable yield ( $B_{MSY}$ ) and the exploitation rate at MSY ( $F_{MSY}$ ).  $B_{MSY}$  corresponds to the level of biomass at which the stock has historically been productive, while  $F_{MSY}$  approximates the exploitation rate observed during periods of high abundance. However, the absolute annual values for biomass ( $B$ ) and the exploitation rate ( $F$ ) estimated by the SPM do not make it possible to distinguish the effects of changes in productivity and fishing pressure on stock dynamics, so they should be interpreted with caution. Their trajectories over the entire series are also informative, and the relationship between the relative biomass ( $B/B_{MSY}$ ) and the relative exploitation rate ( $F/F_{MSY}$ ) could also serve as a guide in establishing a level of fishing removals that will reduce the risk of overfishing. The model may not fully capture the medium- and long-term effects of the fishery on stock dynamics.

## CONCLUSION

The results obtained show that the model had a good fit to the data and was able to reliably track the trajectories of stock biomass and exploitation rates. The results were consistent with those of previous stock assessments, confirming that the scallop stock has been declining for a number of years and, in 2022, reached the lowest biomass values observed since the beginning of the time series (for landings) in 1987 (Table 6).

The estimation of a number of values, such as maximum sustainable yield (MSY), the exploitation rate at MSY ( $F_{MSY}$ ), the biomass at MSY ( $B_{MSY}$ ) as well as  $B_t/B_{MSY}$  and  $F_t/F_{MSY}$ , will be extremely useful in developing the precautionary approach.

This model represents a positive step forward in the assessment of scallop stocks in Area 16E. However, as with any model, caution must be exercised when applying the model to ecosystem

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conditions outside the range of those already observed, and ongoing assessments of its effectiveness will be required.

In summary, the model indicates that stock biomass has been declining, reaching the lowest value ever recorded (99.69 t) in 2022 (Table 6). In addition, a limit reference point (LRP) has been established at 40% of the theoretical biomass at maximum sustainable yield ( $B_{MSY}$ ), or 182.8 t. The stock has likely been in the critical zone of the precautionary approach since 2008 (figures 9 and 12).

The removal rate estimated by the model indicates that fishing effort has likely exceeded the level that the stock can withstand since 1990, except in 2010 and 2014. Since the stock is in the critical zone, a rebuilding plan for Area 16E is currently being developed.

## ACKNOWLEDGEMENTS

We would like to thank Mathieu Boudreau, Daniel Duplisea and Andrew Smith for their valuable advice on the Bayesian surplus production model fit to the Iceland scallop stock in Area 16E. We would also like to thank our colleagues at the Bedford Institute of Oceanography for their constructive discussions on scallops and stock assessment models. We are also grateful to Daniel Duplisea and Andrew Smith for reviewing this document.

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## TABLES

*Table 1. Annual landings (tonnes of meat) and annual values of the biomass indices (g/m<sup>2</sup>) for Iceland scallop (≥ 70 mm) used in the surplus production model for Area 16E.*

| Year | Landing (t) | Biomass Indices            |                           |                           |                           |
|------|-------------|----------------------------|---------------------------|---------------------------|---------------------------|
|      |             | Normal (g/m <sup>2</sup> ) | S2003 (g/m <sup>2</sup> ) | S2004 (g/m <sup>2</sup> ) | S2007 (g/m <sup>2</sup> ) |
| 1987 | 42.3        | -                          | -                         | -                         | -                         |
| 1988 | 53.5        | -                          | -                         | -                         | -                         |
| 1989 | 61.1        | -                          | -                         | -                         | -                         |
| 1990 | 123.7       | 2.2344                     | -                         | -                         | -                         |
| 1991 | 132.5       | *                          | -                         | -                         | -                         |
| 1992 | 116.1       | -                          | -                         | -                         | -                         |
| 1993 | 79.8        | -                          | -                         | -                         | -                         |
| 1994 | 78.8        | -                          | -                         | -                         | -                         |
| 1995 | 65.6        | -                          | -                         | -                         | -                         |
| 1996 | 71.5        | 2.4526                     | -                         | -                         | -                         |
| 1997 | 57.4        | -                          | -                         | -                         | -                         |
| 1998 | 57.2        | 1.3074                     | -                         | -                         | -                         |
| 1999 | 57.1        | -                          | -                         | -                         | -                         |
| 2000 | 56.1        | 2.1028                     | -                         | -                         | -                         |
| 2001 | 56.4        | 2.1480                     | -                         | -                         | -                         |
| 2002 | 33.6        | -                          | -                         | -                         | -                         |
| 2003 | 55.1        | 1.8256                     | 4.6586                    | -                         | -                         |
| 2004 | 53.2        | 1.4555                     | 3.2419                    | 4.0804                    | -                         |
| 2005 | 48.7        | 1.1652                     | 2.2105                    | 3.2583                    | -                         |
| 2006 | 52.1        | -                          | -                         | -                         | -                         |
| 2007 | 36.7        | 0.9071                     | 4.1951                    | 2.2055                    | 2.6866                    |
| 2008 | 30.3        | 0.9441                     | 3.6840                    | 1.6325                    | 2.1230                    |
| 2009 | 21.3        | -                          | 2.7395                    | 2.5180                    | -                         |
| 2010 | 10.9        | 0.6697                     | 1.9408                    | 2.0113                    | 1.8005                    |
| 2011 | 11.9        | -                          | -                         | -                         | -                         |
| 2012 | 16.2        | 0.3922                     | 2.2420                    | 2.7239                    | 2.0428                    |
| 2013 | 14.9        | -                          | -                         | -                         | -                         |
| 2014 | 6.6         | 0.3736                     | 1.6044                    | 1.2365                    | 1.4900                    |
| 2015 | 12.2        | -                          | -                         | -                         | -                         |
| 2016 | 12.9        | 0.6852                     | 1.8138                    | 1.2362                    | 1.7918                    |
| 2017 | 15.7        | -                          | -                         | -                         | -                         |
| 2018 | 15.1        | 0.8880                     | 2.8250                    | 1.2346                    | 1.6032                    |
| 2019 | 12.0        | 0.4972                     | 2.4650                    | 0.6564                    | *                         |
| 2020 | 14.1        | -                          | -                         | -                         | -                         |
| 2021 | 9.2         | -                          | -                         | -                         | -                         |
| 2022 | 10.6        | 0.5260                     | 2.6484                    | 1.0550                    | 1.1134                    |

\* Data removed due to abnormally low values (see the DATA USED section).

Table 2. List of stations in the research survey included in each index used in the modelling.

| <b>N</b> | <b>S2003</b> | <b>S2004</b> | <b>S2007</b> |
|----------|--------------|--------------|--------------|
| A5       | A12          | D10          | C10          |
| A6       | A13          | D11          | C11          |
| A7       | D3           | D12          | R1           |
| A8       | D4           | D13          | R2           |
| A9       | D5           | F19          | R3           |
| A11      | D6           | F20          | R4           |
| C1       | D7           | F21          | -            |
| C2       | D8           | F22          | -            |
| C3       | D9           | -            | -            |
| C4       | F15          | -            | -            |
| C5       | F16          | -            | -            |
| C6       | F17          | -            | -            |
| C7       | F18          | -            | -            |
| C8       | Q4           | -            | -            |
| C9       | -            | -            | -            |
| D1       | -            | -            | -            |
| D2       | -            | -            | -            |
| F1       | -            | -            | -            |
| F2       | -            | -            | -            |
| F3       | -            | -            | -            |
| F4       | -            | -            | -            |
| F5       | -            | -            | -            |
| F6       | -            | -            | -            |
| F7       | -            | -            | -            |
| F8       | -            | -            | -            |
| F9       | -            | -            | -            |
| F10      | -            | -            | -            |
| F11      | -            | -            | -            |
| F12      | -            | -            | -            |
| F13      | -            | -            | -            |
| F14      | -            | -            | -            |
| H1       | -            | -            | -            |
| H2       | -            | -            | -            |
| H3       | -            | -            | -            |
| H4       | -            | -            | -            |
| Q1       | -            | -            | -            |
| Q2       | -            | -            | -            |
| Q3       | -            | -            | -            |

Table 3. Prior distributions used in the base model for the Iceland scallop stock in Area 16E.

| Parameter                      | Parameter distribution | Prior distribution | Distribution used by JABBA | Sensitivity test performed |
|--------------------------------|------------------------|--------------------|----------------------------|----------------------------|
| $r$                            | 0.05-0.3               | Uniform            | Log-normal                 | No                         |
| $K$                            | 500-1000               | Uniform            | Log-normal                 | Yes                        |
| $B_1/K$ mean                   | 0.5 (c.v. 0.5)         | Log-normal         | Log-normal                 | Yes                        |
| $\sigma_{\eta}^2$ (igamma)     | 4, 0.01                | Inverse gamma      | Inverse gamma              | No                         |
| $\sigma_{fix}^2$ (fixed.obsE)  | 0.2                    | Fixed              | Fixed                      | No                         |
| $\sigma_{est,t}^2$ (sigma.est) | 0.2, 0.001             | Inverse gamma      | Inverse gamma              | No                         |
| CV for catches                 | 0.1                    | Fixed              | Fixed                      | No                         |

Table 4. Statistics for the fit of the model for the Iceland scallop stock in Area 16E. SDNR is the standard deviation of normalized residuals, RMSE is the root mean square error, and DIC is the deviance information criterion.

| Statistics | Value  |
|------------|--------|
| SDNR       | 1.31   |
| RMSE       | 30.1   |
| DIC        | -220.9 |

Table 5. Posterior distributions used in the base model for the Iceland scallop stock in Area 16E.

| Parameter          | Median  | CI Low  | CI High  |
|--------------------|---------|---------|----------|
| $K$                | 913.992 | 699.304 | 1188.817 |
| $r$                | 0.175   | 0.078   | 0.314    |
| $B_1/K$            | 0.780   | 0.413   | 1.275    |
| $F_{MSY}$          | 0.087   | 0.039   | 0.157    |
| $B_{MSY}$          | 456.996 | 349.652 | 594.409  |
| $MSY$              | 39.916  | 18.246  | 67.432   |
| $B_{2022}/B_{MSY}$ | 0.217   | 0.148   | 0.343    |
| $F_{2022}/F_{MSY}$ | 1.224   | 0.846   | 2.122    |
| $q.1$ (N)          | 0.005   | 0.003   | 0.007    |
| $q.2$ (S2003)      | 0.017   | 0.012   | 0.026    |
| $q.3$ (S2004)      | 0.012   | 0.008   | 0.018    |
| $q.4$ (S2007)      | 0.014   | 0.009   | 0.020    |
| $\sigma_{\eta}^2$  | 0.004   | 0.001   | 0.016    |

Table 6. Estimated trajectories for the Iceland scallop stock in Area 16E generated by the model.

| <b>Year</b> | <b>Biomass (t)</b> | <b>F</b> | <b>B/40%B<sub>MSY</sub></b> | <b>F/F<sub>MSY</sub></b> | <b>B/B<sub>0</sub></b> |
|-------------|--------------------|----------|-----------------------------|--------------------------|------------------------|
| 1987        | 723.771            | 0.058    | 3.959                       | 0.699                    | 0.788                  |
| 1988        | 712.856            | 0.075    | 3.900                       | 0.886                    | 0.780                  |
| 1989        | 688.575            | 0.089    | 3.767                       | 1.029                    | 0.758                  |
| 1990        | 662.200            | 0.187    | 3.623                       | 2.149                    | 0.732                  |
| 1991        | 601.254            | 0.220    | 3.289                       | 2.536                    | 0.662                  |
| 1992        | 529.123            | 0.219    | 2.895                       | 2.527                    | 0.583                  |
| 1993        | 471.145            | 0.169    | 2.577                       | 1.952                    | 0.517                  |
| 1994        | 446.366            | 0.177    | 2.442                       | 2.041                    | 0.489                  |
| 1995        | 420.010            | 0.156    | 2.298                       | 1.803                    | 0.460                  |
| 1996        | 404.302            | 0.177    | 2.212                       | 2.034                    | 0.443                  |
| 1997        | 373.455            | 0.154    | 2.043                       | 1.773                    | 0.409                  |
| 1998        | 355.135            | 0.161    | 1.943                       | 1.854                    | 0.389                  |
| 1999        | 349.030            | 0.164    | 1.909                       | 1.884                    | 0.381                  |
| 2000        | 342.152            | 0.164    | 1.872                       | 1.898                    | 0.372                  |
| 2001        | 325.487            | 0.173    | 1.781                       | 1.999                    | 0.354                  |
| 2002        | 297.518            | 0.113    | 1.628                       | 1.301                    | 0.323                  |
| 2003        | 290.327            | 0.190    | 1.588                       | 2.171                    | 0.317                  |
| 2004        | 259.248            | 0.205    | 1.418                       | 2.343                    | 0.283                  |
| 2005        | 228.950            | 0.213    | 1.252                       | 2.428                    | 0.250                  |
| 2006        | 211.742            | 0.246    | 1.158                       | 2.813                    | 0.231                  |
| 2007        | 186.987            | 0.196    | 1.023                       | 2.249                    | 0.204                  |
| 2008        | 167.714            | 0.180    | 0.917                       | 2.072                    | 0.183                  |
| 2009        | 151.802            | 0.140    | 0.830                       | 1.616                    | 0.165                  |
| 2010        | 137.549            | 0.079    | 0.752                       | 0.905                    | 0.150                  |
| 2011        | 134.542            | 0.088    | 0.736                       | 1.009                    | 0.147                  |
| 2012        | 130.775            | 0.124    | 0.715                       | 1.416                    | 0.143                  |
| 2013        | 120.622            | 0.124    | 0.660                       | 1.413                    | 0.132                  |
| 2014        | 111.433            | 0.059    | 0.610                       | 0.672                    | 0.122                  |
| 2015        | 118.120            | 0.103    | 0.646                       | 1.175                    | 0.129                  |
| 2016        | 119.422            | 0.108    | 0.653                       | 1.237                    | 0.130                  |
| 2017        | 120.047            | 0.131    | 0.657                       | 1.491                    | 0.131                  |
| 2018        | 117.573            | 0.129    | 0.643                       | 1.472                    | 0.128                  |
| 2019        | 107.363            | 0.112    | 0.587                       | 1.278                    | 0.117                  |
| 2020        | 105.356            | 0.134    | 0.576                       | 1.531                    | 0.115                  |
| 2021        | 100.450            | 0.092    | 0.550                       | 1.053                    | 0.110                  |
| 2022        | 99.693             | 0.106    | 0.545                       | 1.224                    | 0.109                  |

## FIGURES



Figure 1. Photo of a sea scallop (left) and an Iceland scallop (right).

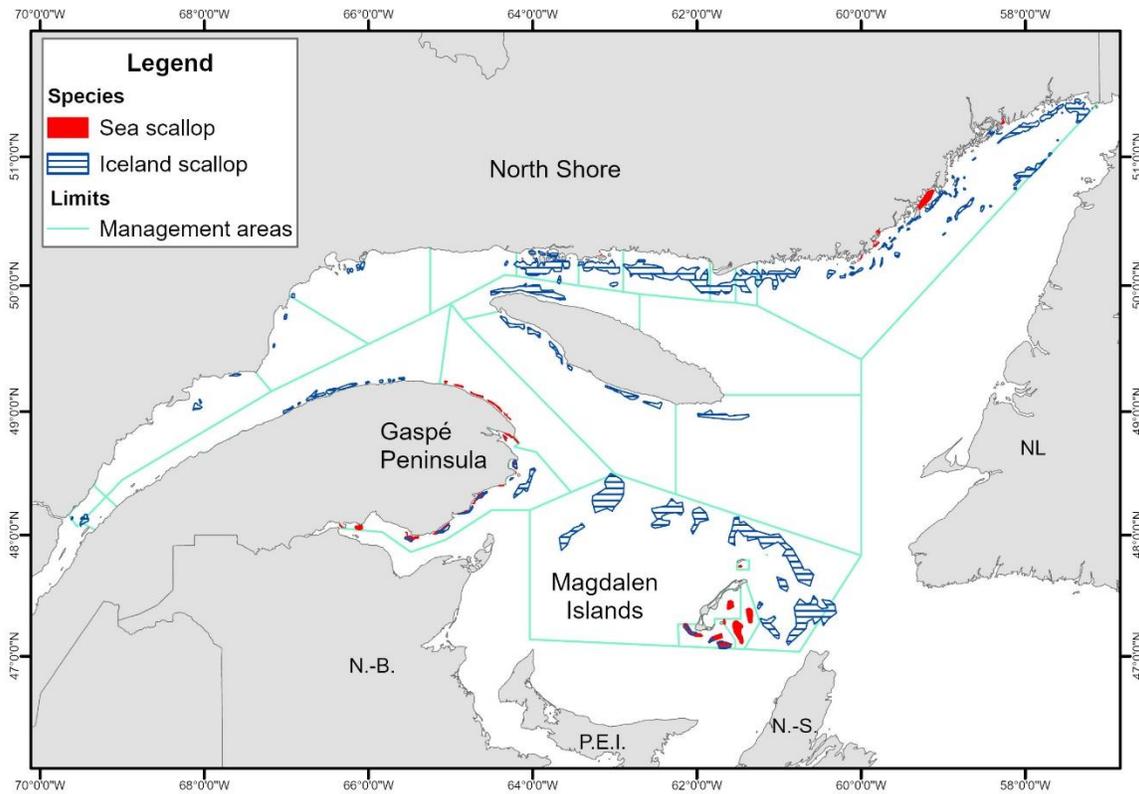


Figure 2. Known distribution of the sea scallop and Iceland scallop in Quebec coastal waters (information sources: logbooks, at-sea sampling, research survey, exploratory fishery and DFO's groundfish survey in the southern Gulf of St. Lawrence).

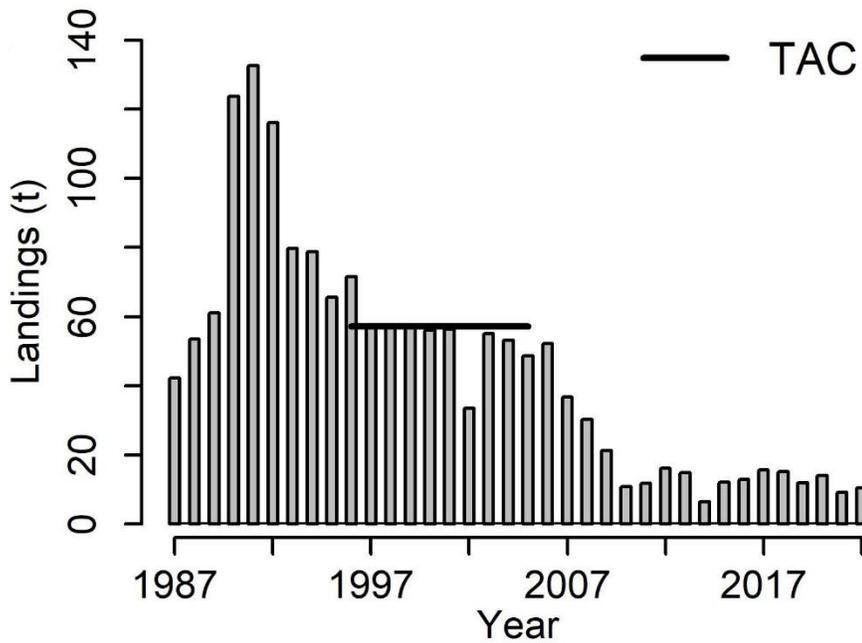


Figure 3. Annual scallop landings (tonnes of meat) in Area 16E.

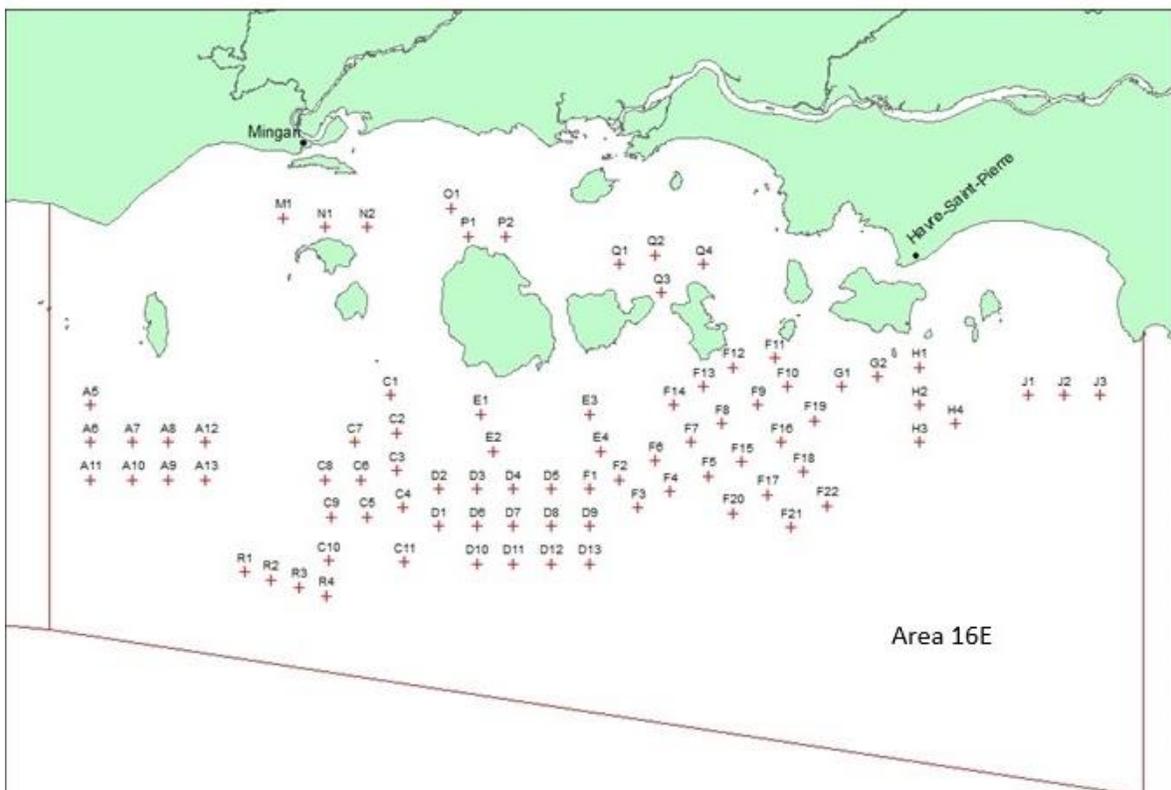


Figure 4. Map of fixed stations sampled during research surveys for scallops in Area 16E since 1990. Note that some stations have been eliminated and others added over the years. All stations included in each index used in the modelling are listed in Table 2.

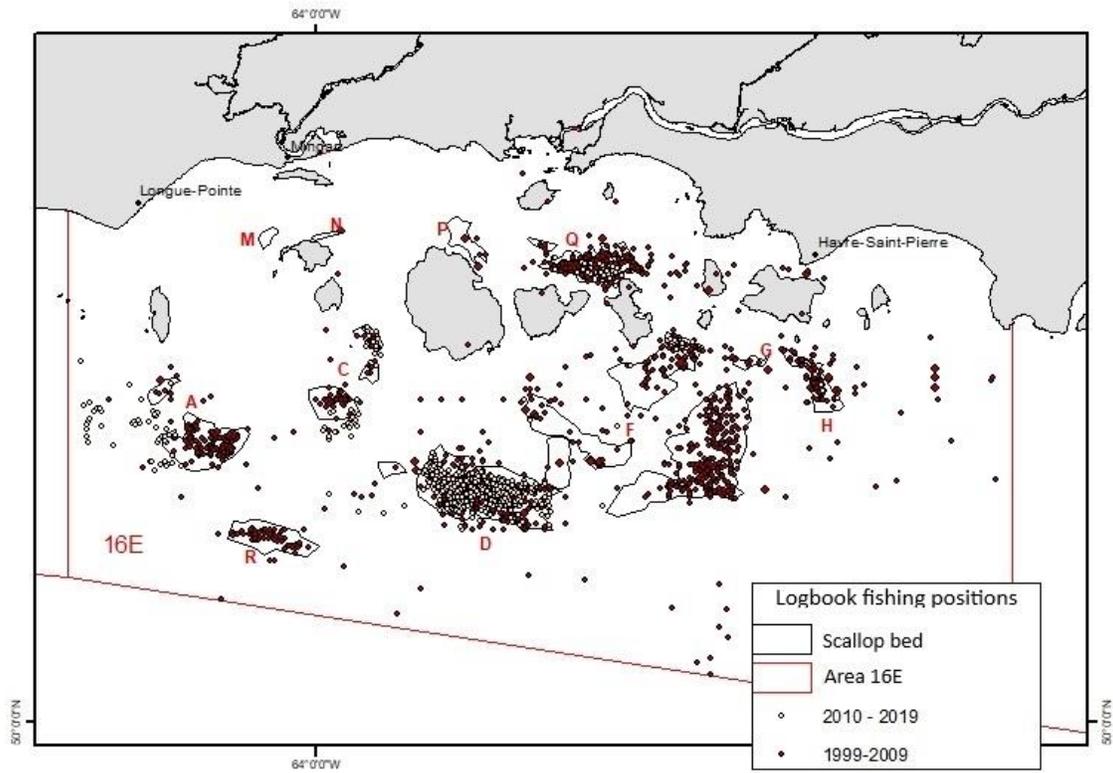


Figure 5. Fishing positions over Iceland scallop beds in Area 16E from 1999 to 2009 obtained from logbooks. The beds retained for modelling are beds A, C, D, F, H, R and Q, which account for the vast majority of fishing activities.

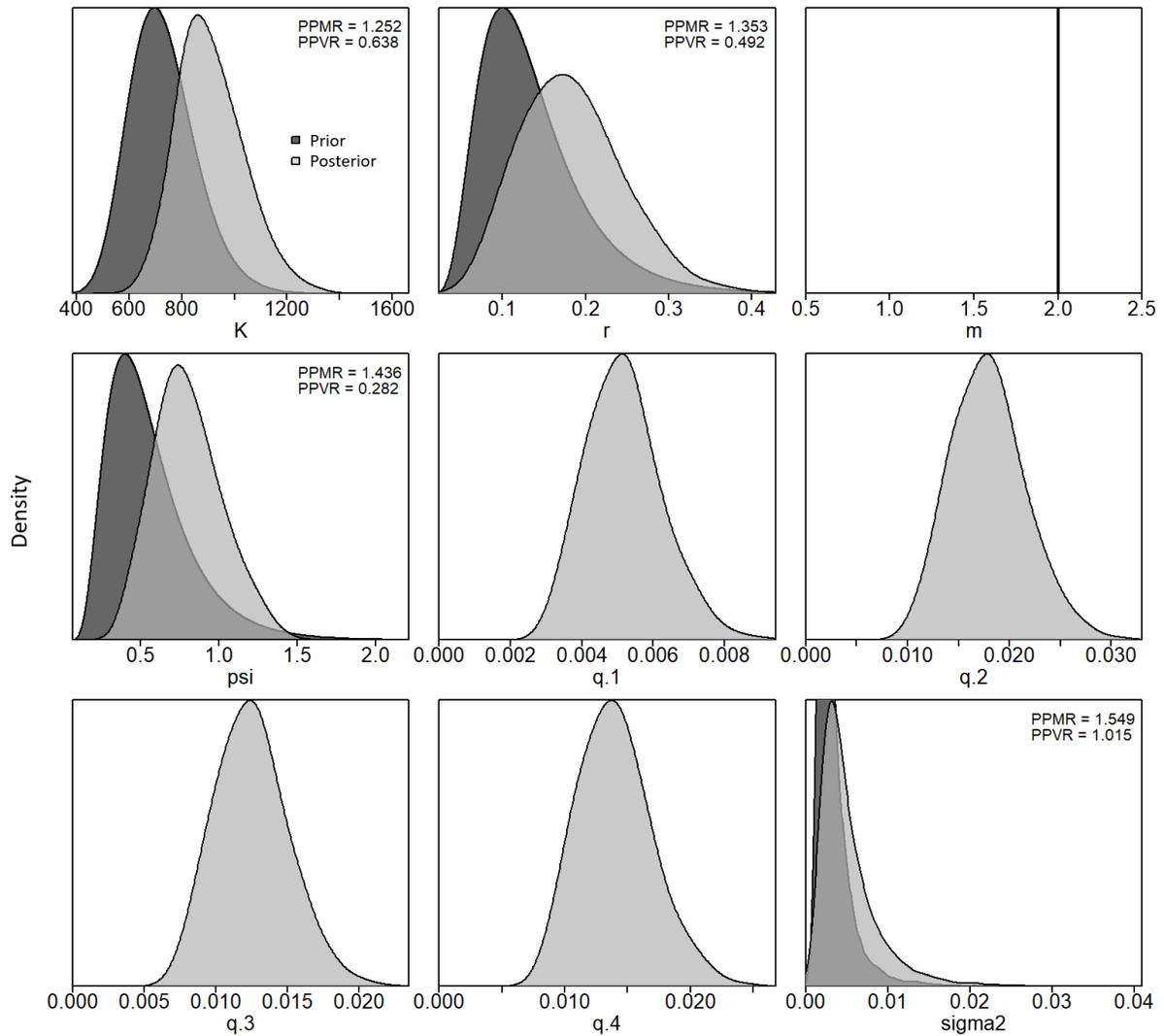


Figure 6. Prior distributions (dark grey) and posterior distributions (light grey) of the parameters used in the base model for Iceland scallop in Area 16E. The parameters examined include carrying capacity ( $K$ ), intrinsic rate of increase ( $r$ ), Schaefer model ( $m = 2$ ), initial depletion in the first year of the time series (biomass as a proportion of carrying capacity in the first year of the time series) ( $\psi = B1/K$ ), the biomass index catchability coefficients ( $N = q.1$ ,  $S2003 = q.2$ ,  $S2004 = q.3$  and  $S2007 = q.4$ ) and the process error variance  $\sigma_{\eta}^2$  ( $\text{sigma2}$ ). Posterior distributions were plotted using generic kernel densities.

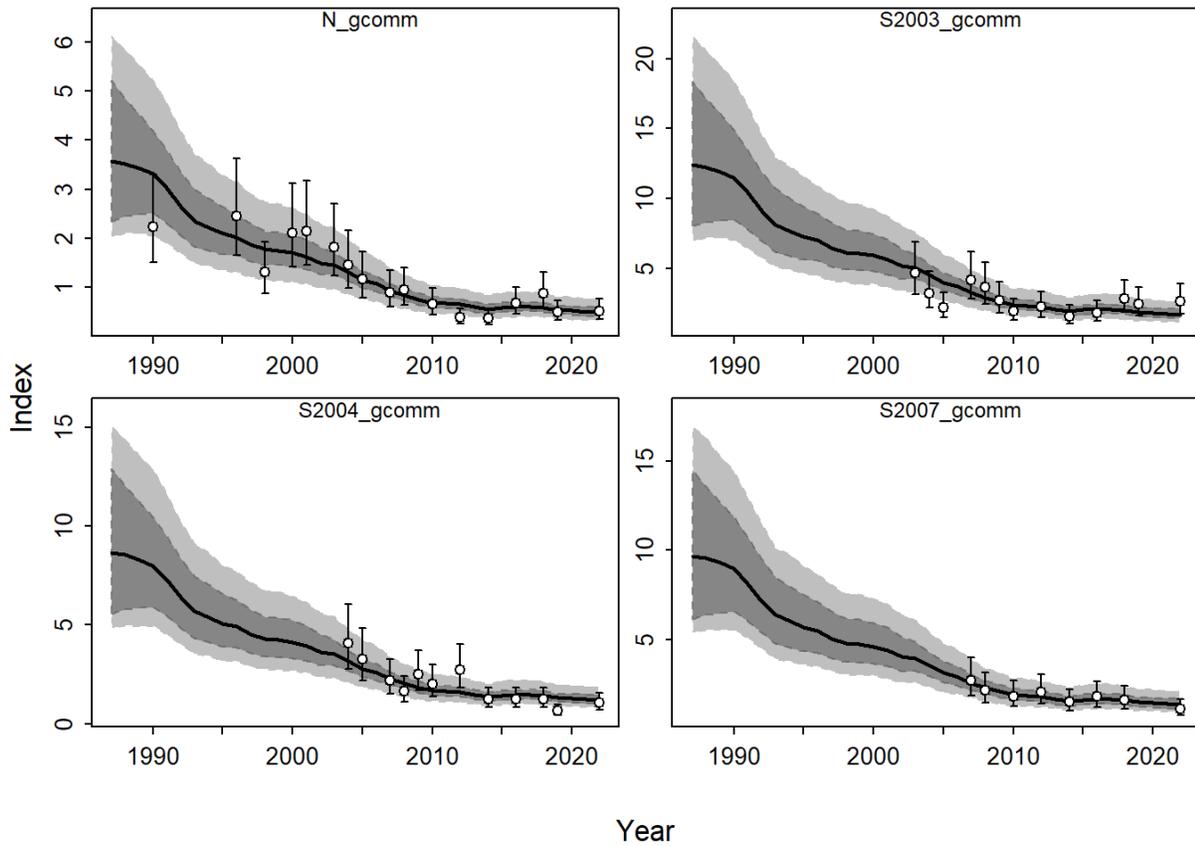


Figure 7. Predicted values compared with observed values for each index in the JABBA model for Iceland scallop in Area 16E. Indices (from left to right and top to bottom): normal stations (N\_gcomm, present since 1990); additional stations in 2003 (S2003\_gcomm); additional stations in 2004 (S2004\_gcomm); and additional stations in 2007 (S2007\_gcomm). Index: catch per unit effort (CPUE,  $g/m^2$ ); white dots: observed data and confidence interval estimated by JABBA; dark grey: biomass estimated and confidence interval estimated by JABBA; and light grey: posterior predictive distribution and confidence interval.

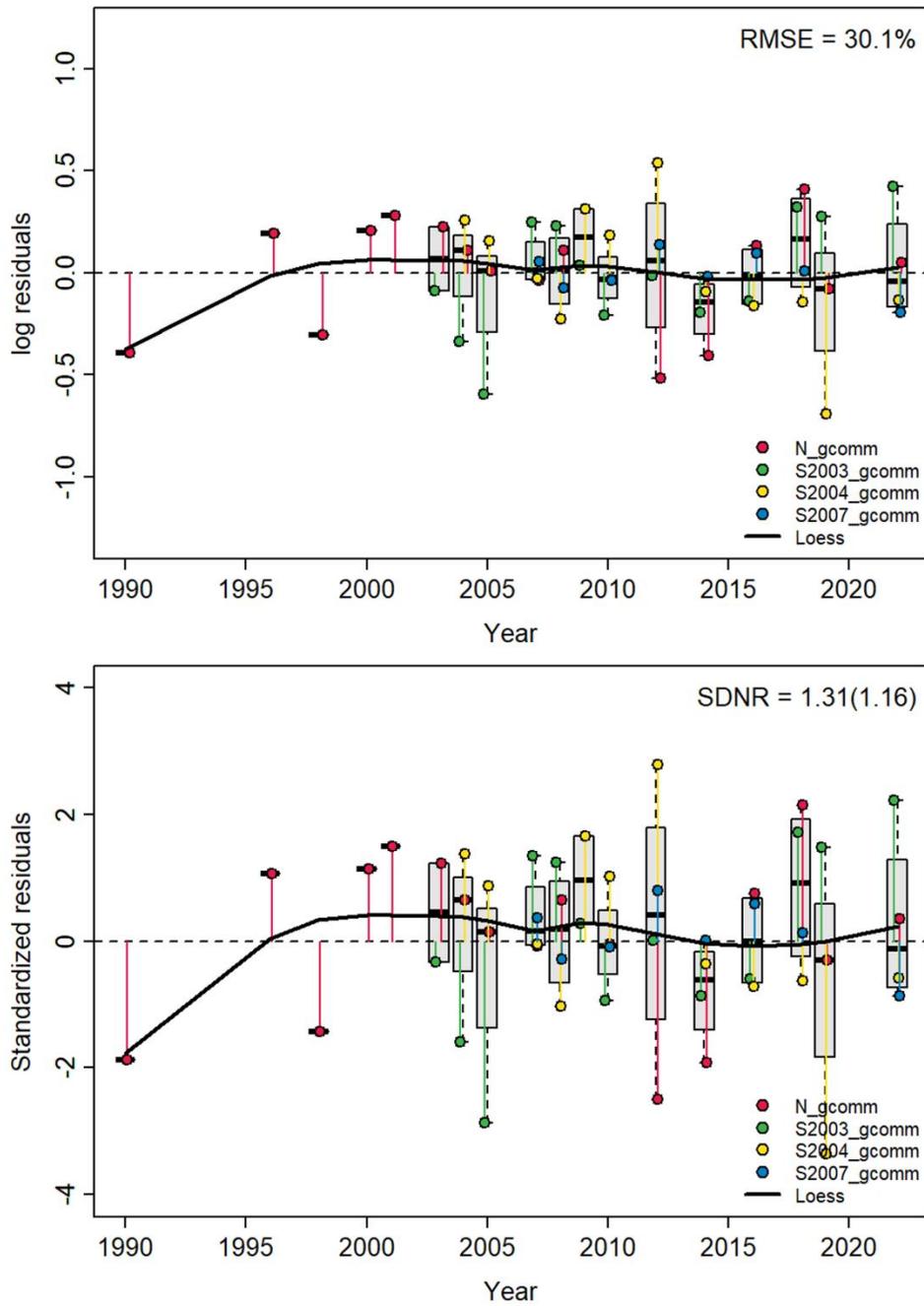


Figure 8. Residual diagnostics (plotted on a log scale on top and standardized scale on bottom) for the JABBA model for Iceland scallop in Area 16E. N: normal stations sampled since 1990; S2003: stations added in 2003; S2004: stations added in 2004; S2007: stations added in 2007; and gcomm: unit ( $\text{g}/\text{m}^2$  of Iceland scallops  $> 70$  mm in size).

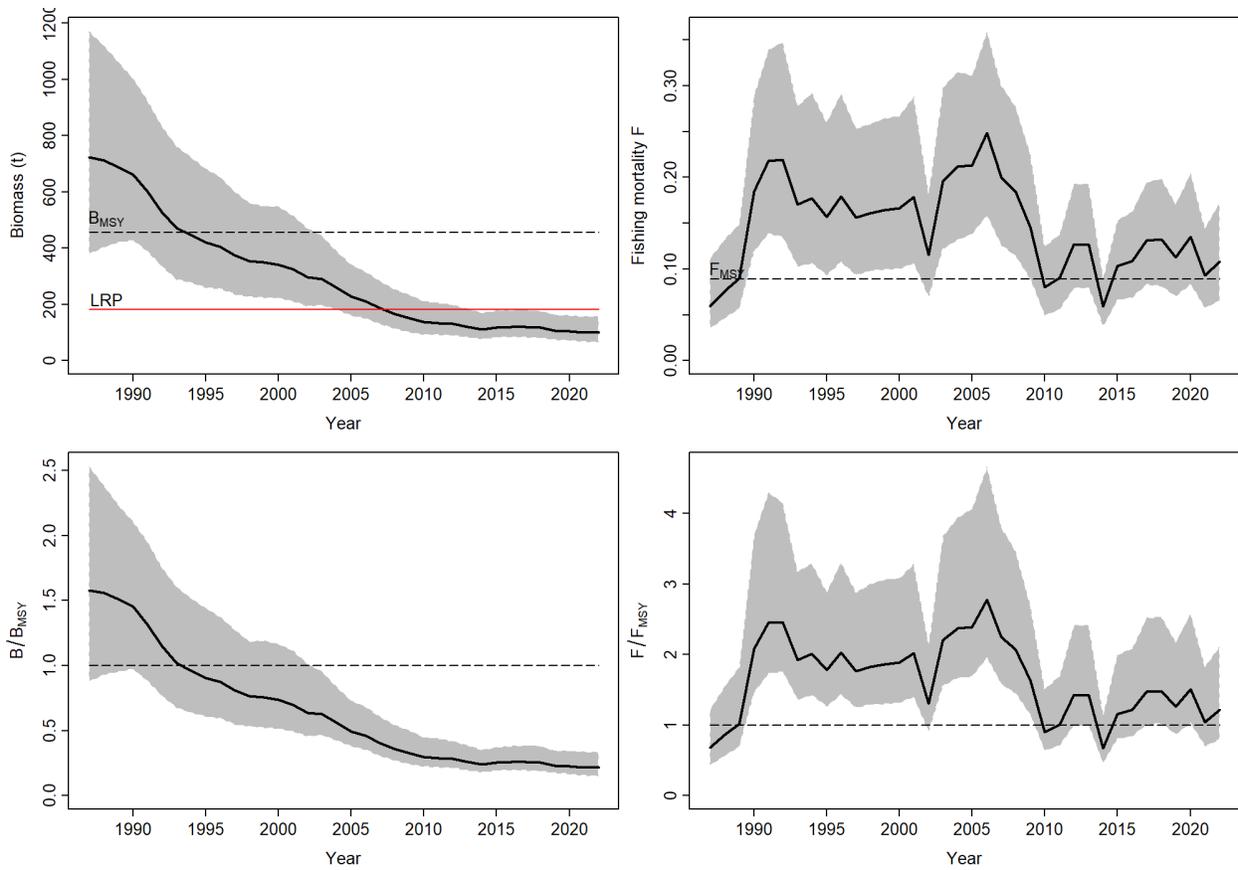


Figure 9. Estimated trajectories for Iceland scallop stock biomass ( $B_t$ ) in Area 16E and fishing mortality ( $F_t$ ), scaled to the maximum sustainable yield ( $B/B_{MSY}$  and  $F/F_{MSY}$ ). The shaded area represents the 95% confidence interval. The red line indicates the limit reference point (LRP) established at 40% of the theoretical biomass at maximum sustainable yield ( $B_{MSY}$ ), i.e., 182.8 tonnes in 2022.

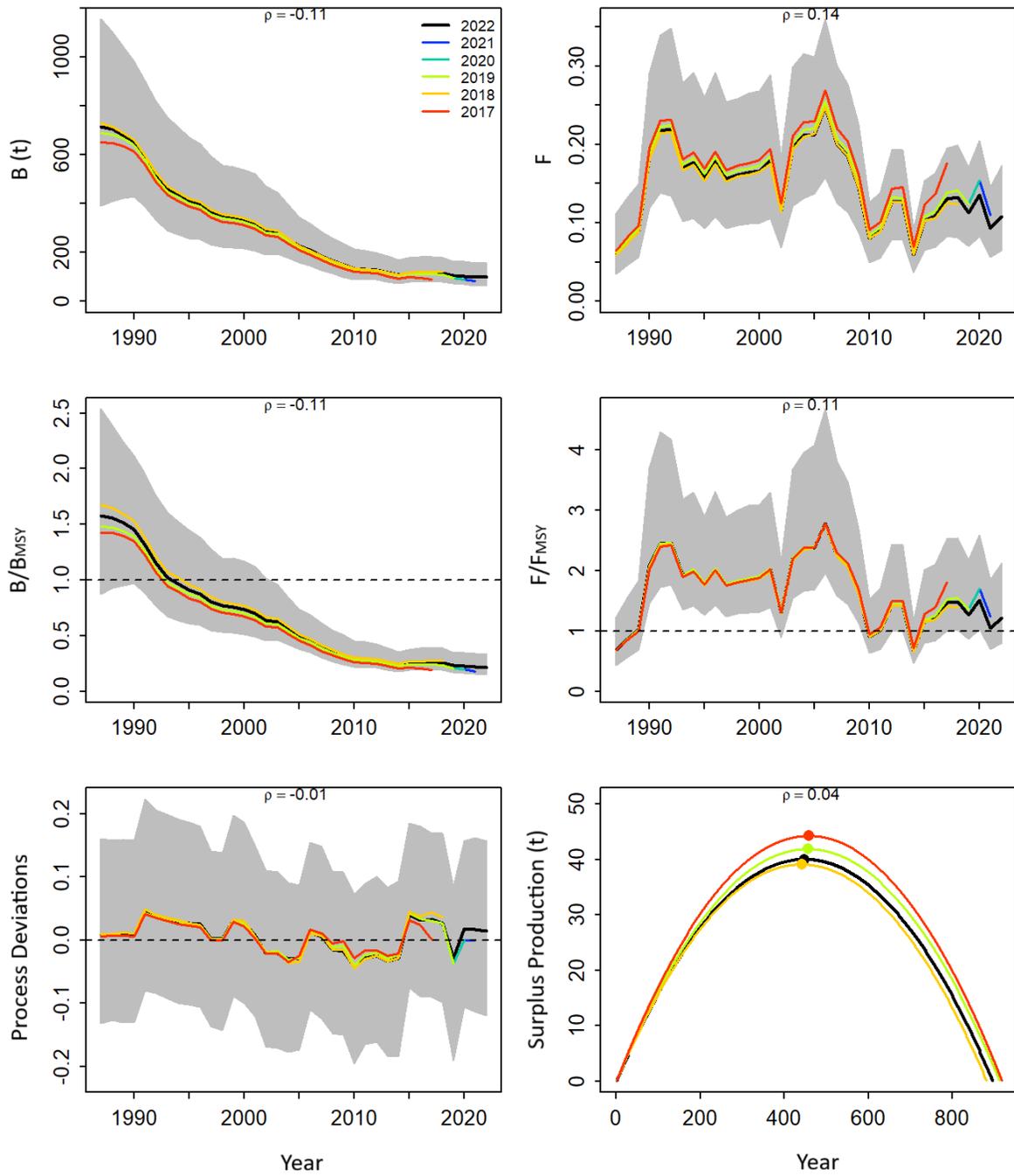


Figure 10. Retrospective analysis for the Iceland scallop stock in Area 16E (2017–2022). The mean Mohn's rho values are shown on each graph.

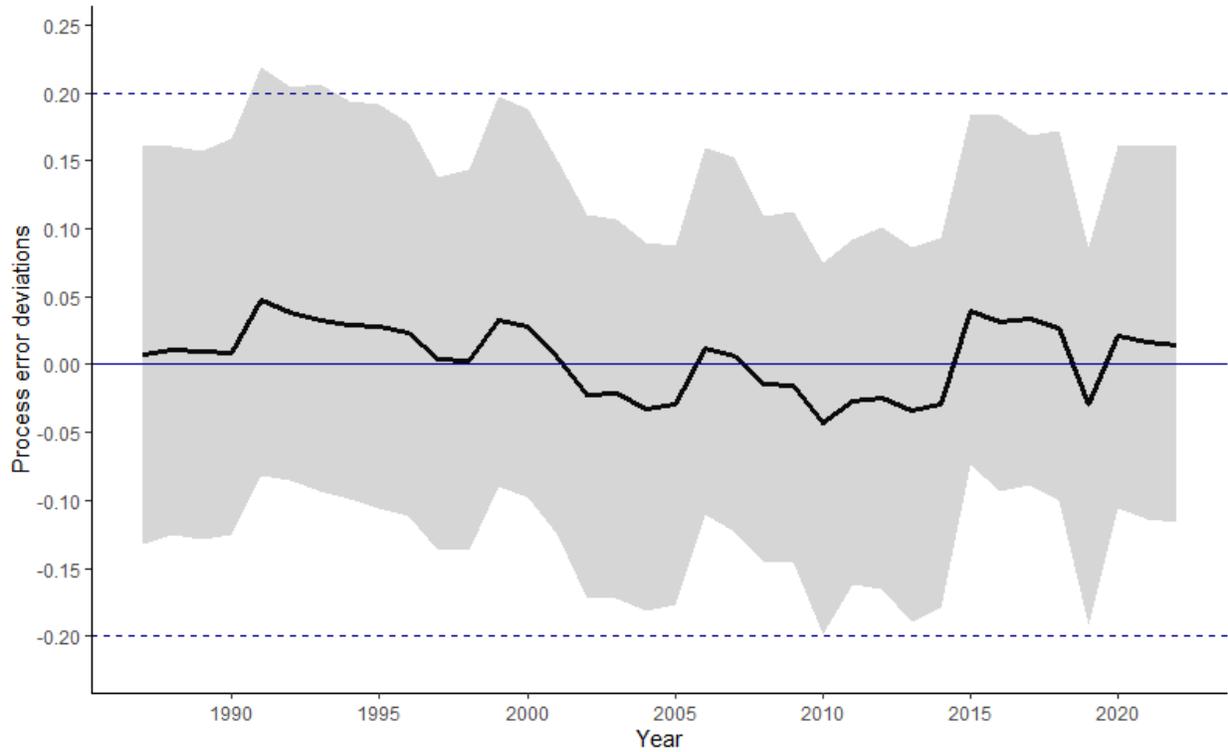


Figure 11. Process error deviation in the Iceland scallop model for Area 16E. The black line represents the median value of the posterior distribution, while the 95% confidence interval is shown in grey. The solid blue line represents the trend for biomass generated by the deterministic portion of the model, while the dashed blue lines are provided to make the graph easier to read.

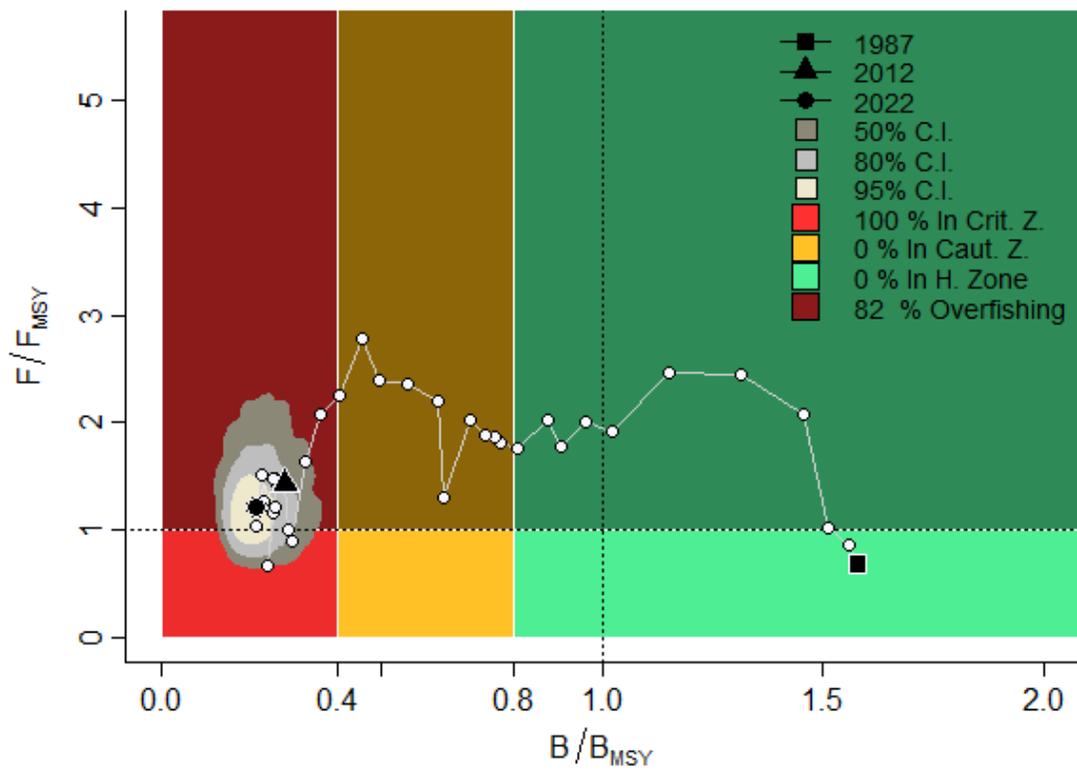


Figure 12. Kobe-type plot for the base case scenario for Iceland scallop in Area 16E. The black line shows the estimated trajectory (1987–2022) between  $F/F_{MSY}$  and  $B/B_{MSY}$ . The grey shaded areas show the confidence intervals for the terminal year (50%, 80% and 95%). The probabilities of the terminal year being located in one of the quadrants are indicated in the legend.

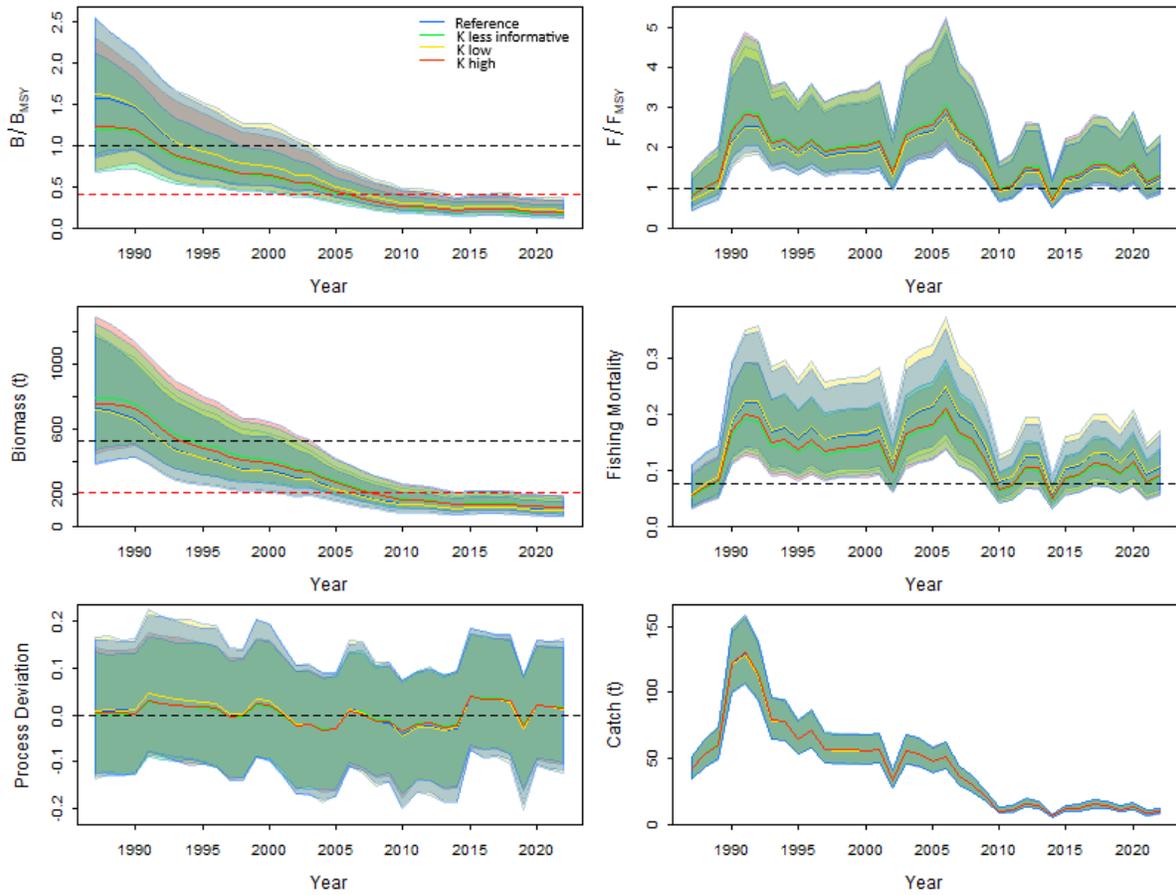


Figure 13. Estimated trajectories for biomass of the Iceland scallop stock in Area 16E ( $B_t$ ) and fishing mortality ( $F_t$ ), scaled according to the maximum sustainable yield ( $B/B_{MSY}$  and  $F/F_{MSY}$ ), process error deviation and landings according to the four K scenarios tested. The shaded areas represent the different 95% confidence intervals for each scenario. The blue dashed lines show the estimated values for maximum sustainable yield and the red dashed lines represent the limit reference point ( $0.4 \cdot B_{MSY}$  and  $0.4 \cdot F_{MSY}$ ).

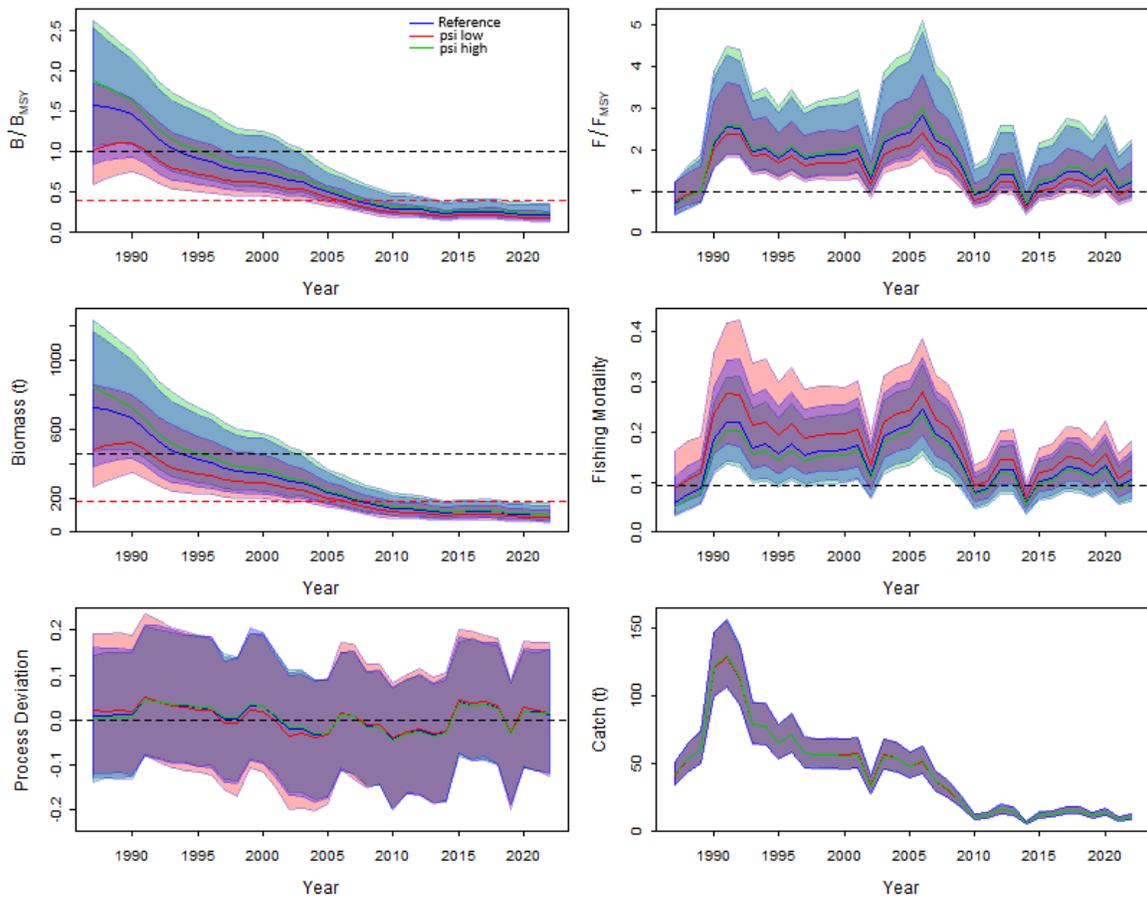


Figure 14. Estimated trajectories for biomass of the Iceland scallop stock in Area 16E ( $B_t$ ) and fishing mortality ( $F_t$ ), scaled according to the maximum sustainable yield ( $B/B_{MSY}$  and  $F/F_{MSY}$ ), process error deviation and landings according to the three  $\psi_1/K$  scenarios tested. The shaded areas represent the different 95% confidence intervals for each scenario. The blue dashed lines show the estimated values for maximum sustainable yield and the red dashed lines represent the limit reference point ( $0.4 \cdot B_{MSY}$  and  $0.4 \cdot B/B_{MSY}$ ).