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September 2020

STOCK ASSESSMENT OF THE SOUTHERN INDIAN OCEAN ST. PAUL AND AMSTERDAM ROCK LOBSTER STOCKS USING BAYESIAN STATE SPACE SURPLUS PRODUCTION MODEL

Fishing campaign 2020-2021



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Southern Fisheries Ecosystem Observation Program (2020) within the BIOPAC team of the Laboratory of Biology of Aquatic Organisms and Ecosystems.

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1. Abstract

Bayesian state-space surplus production models were fitted to Amsterdam and St. Paul rock lobster (*Jasus paulensis*) catch and CPUE data using the open-source stock assessment tool JABBA. The results of the reference case models indicated that MSY estimates lied between 182 and 258 tons for Amsterdam and 208 and 352 tons for St. Paul rock lobster. Stock status trajectories for both rock lobster stocks started from an underexploited state and moved from of a period of unsustainable fishing in the beginning of the 1980s. Both stocks recovered in the 1990s leading to a > 95% and > 85% probability of stocks biomass in 2019/2020 being above level that produce MSY and fishing mortality rates below sustainable exploitation levels for Amsterdam and St. Paul respectively. Finally, based on the sensitivity analysis, all alternative scenarios combined lead to a 95% and 89% probability that the stock of Amsterdam and St. Paul were below sustainable bounds.

2. Introduction

St. Paul and Amsterdam (SPA) islands are part of the French Southern and Antarctic Territories (TAAF) and are located in the subtropical zone of the South Indian Ocean (Figure 1). Initially focused on the exploitation of fur seals (*Arctocephalus tropicalis*) and demersal fishes, these islands have been exploited annually for rock lobsters (*Jasus paulensis*) since 1948.

In the recent year, the fishing fleet is composed of a single mother ship, the “Austral 2”, which targets and lands mainly rock lobster fished from 4 coastal (operating in depth inferior to 50 m) canots (doris) setting wooden traps in the kelp zone and 2 pilothouse fishing boats (“caseyeurs”) in the deepest area (operating in depth from 70 to 400 m) with line of 20 steel traps. Rock lobsters are transhipped and weighted to the mother ship where catches are proceeded on the on-board factory. Fishing takes place during the austral summer between the end of November of the year t and May of the year $t + 1$ during which time the vessel makes two fishing trips of approximately the same duration (less than 2 months).

The fishery is managed by setting annual total allowable catches (TAC) for the rock lobster as well as technical prescriptions to control the fishing effort (e.g. fishing period, authorized fishing gear, mandatory fishing logbook, trap mesh size, legal size of first catch, control of discards) with the support of onboard fishing controllers on 100% of the fishing trips and landing controls.

The key indicator for setting TAC is the Catch per Unit Effort (CPUE) trend, based on data of lobster catches per trap set (by weight) and the numbers of traps set recorded. Until now, the

nominal CPUE was used directly without standardisation based on the rationale that the fishing period, area and method have been kept throughout the time series. The fishery is managed to maintain the CPUE at the level of the long-term average leading to TAC which has historically fluctuated between 350 and 400 tons per year.

This document presents the first stock assessment results for Amsterdam and St. Paul rock lobster stocks based on the Bayesian state-space Surplus Production Model (SPM) framework, JABBA (Just Another Bayesian Biomass Assessment; Winker et al., 2018a) using long catch and standardized CPUE time series from 1981 to 2019.

3. Methodology

Fishery data

Catch and CPUE time series were available from 1981 to 2019. Relative abundance indices were used in the form of standardized CPUE time series for each Island (Selles, 2020) which were assumed to be proportional to biomass. The standardizing CPUE series was based on fishing year, fishing period, fishing area and fishing year-area interactions which corresponds strictly to the operation of two fleets (Figure 2, 3).

State-space surplus production model

The stock assessment was implemented using the Bayesian state-space surplus production model framework JABBA (Winker et al., 2018a) and based on the generalized Pella-Tomlinson surplus production function of the form:

$$g(B_t) = \frac{r}{m-1} B_t \left[1 - \left(\frac{B_t}{K} \right)^{m-1} \right]$$

where r is the intrinsic rate of population increase at time t , K is the carrying capacity or the unfished (virgin) biomass level at equilibrium and m is a shape parameter that determines at which B/K ratio the maximum surplus production is attained.

Based on the parameterization by Meyer and Millar (1999), the process equation was rewritten into a stochastic population model with population state variables expressed as a depletion biomass formulated as the proportion of the virgin biomass ($P_t = \frac{B_t}{K}$). The initial biomass depletion level was estimated by introducing model parameter (φ). The stochastic form of the state process equation is given by:

$$P_1 = \varphi e^{\eta t}; \text{ for } t = 1$$

$$P_t = \left[P_{t-1} + rP_{t-1}(1 - P_{t-1}^m) - \frac{C_t}{K} \right] e^{\eta_t}; \text{ for } t = 2, \dots, n$$

where η_t is the process error, with $\eta_t \sim \text{Normal}(0, \sigma_\eta^2)$, r is the intrinsic rate of population increase, K denotes the unfished biomass at theoretical carrying capacity, C_t is the catch in year t and φ is the initial biomass depletion.

The observation model connects the state process to abundance index I_t (CPUE series) for year t , assuming I_t is proportional to biomass. The observation equation is given by:

$$I_t = qB_t e^{\epsilon_t}$$

where, q is the catchability coefficient and ϵ_t is the observation error, with $\epsilon_t \sim \text{Normal}(0, \sigma_\epsilon^2)$.

The full Bayesian state-space model specification requires a joint probability distribution over all unobservable hyper-parameters $\theta(K, r, q, \varphi, \sigma_\eta^2, \sigma_\epsilon^2)$ assuming independent priors and the n process errors relating to the vector of unobserved states $\eta(\eta_1, \dots, \eta_n)$, together with all observable data in the form of the relative abundance indices $I = (I_1, \dots, I_n)$.

Priors

For the reference case model (Table 1) priors for r and K were kept uninformative to convey minimal prior information on the parameter estimates. For K , a lognormal was implemented as ranges of minimum and maximum of plausible values for a uniform distribution (Froese et al., 2016) for each island. A virgin biomass between 500 t and 10,000 tons was selected and is equivalent to a mean value of 5250 t and a CV of 118%. The lower limit was set above the maximum observed catch since the beginning of the time series. For r the minimum and maximum values were set to 0.1 and 1 to approximate prior ranges of medium resilience species (Froese et al., 2016) which resulted in a mean of 0.55 and a CV of 85%.

The initial depletion biomass (φ) was defined by a lognormal prior with a mean of 0.6 and a CV of 83% assuming a lower exploitation rate before 1981 based on the reconstruction of the catch series made by Pruvost et al. (2015).

The total observation variance σ_ϵ^2 were separated into two components¹ to distinguish between fixed observation error $\sigma_{se,t}^2$ estimated from standardised CPUE (Selles, 2020) and estimable variance σ_{est}^2 where the prior was kept uninformative with an inverse-gamma distribution with

¹ Fixed input variance was set to 0.

both gamma scaling parameters set to 0.001. Similarly, catchability parameters were formulated as uninformative uniform priors with an inverse-gamma distribution.

Process error (σ_{η}^2) was freely estimated using a non-informative inverse-gamma distribution with gamma scaling parameters set to 0.001.

Sensitivity analysis

SPMs structural and biological uncertainty are represented in the form of parameters K , r and the shape m of the production function, where Schaefer ($m = 2$) and Fox ($m \rightarrow 1$) formulations are the most common choices. Given that K was estimated with priors which convey very little information, we assumed that the main source biological uncertainty is linked to r and structural uncertainty of the model can be attributed to the choice of m .

To capture this uncertainty, we fitted the reference case model over a range of informative priors for r which assume low and high resilience hypotheses (Froese et al., 2016) and fixed values for $BMSY/K$ which cover Fox and Schaefer models (Table 2).

Model fitting and Diagnostics

The Bayesian State-space surplus production model JABBA is implemented in R (R Development Core Team, <https://www.r-project.org/>) with JAGS interface (Plummer, 2003) through ‘r2jags’ library (Su & Yajima, 2012) to estimate the Bayesian posterior distributions of all quantities of interest by means of a Markov Chains Monte Carlo (MCMC) simulation. In this study, two MCMC chains were used. The model was run for 30,000 iterations, sampled with a burn-in period of 5,000 for each chain. Basic diagnostics of model convergence included visualization of the MCMC chains throughout trace-plots as well as Heidelberger and Welch (Heidelberger & Welch, 1992) and (Geweke, 1992) and Gelman and Rubin (1992) diagnostics as implemented in the coda package.

To evaluate CPUE fits, the model predicted CPUE indices were compared to the observed CPUE. Residual plots were also examined, and the randomness of model residuals was evaluated by means of the Root-Mean-Squared-Error (RMSE). The different models run for the sensitivity analysis were compared using the Deviance Information Criterion (DIC).

Biological reference points, projection and phase plots

For SPM, harvest management measures can be derived directly from the expression of $g(B_t)$ (see Winker et al., 2018b), including Maximum Sustainable Yield (MSY), the fishing mortality corresponding to MSY (F_{MSY}); the ratio of the spawning stock biomass to MSY (B/B_{MSY}) and the

ratio of the fishing mortality to MSY (F/F_{MSY}). These parameters were used for determining stock status trajectories using ‘Kobe plots’.

To explore the potential total allowable catch (TAC) levels, the model was used to predict the stock status in the form of biomass depletion (B/K) for different TAC over a period of 10 years.

4. Results

Catch and CPUE

For both islands, catches decreased rapidly in the beginning of the time series starting from approximately 300 tons and reaching 159 tons in 1990 and 152 tons in 1989 for Amsterdam and St. Paul respectively (Figure 2, 3). This period was followed by gradual increases (with peaks and troughs) between approximately 1990 and the early 2000s for Amsterdam and 2015 for St. Paul. For Amsterdam island the total catch showed an overall decrease during the last decade with a slight increase in the last year reaching 151 tons in 2019. Since 2010 annual catches were 144 and 222 tons in average for Amsterdam and St. Paul respectively.

Standardized CPUE (Figure 4, 5) followed in average the same trend that the nominal CPUE showing a sharply decrease of the abundance until 1989 and a gradual increase with (with peaks) until 2015. The last years series showed a dissimilarity between the two series with the standardized CPUE well above approaching the highest recorded level of abundance since 1980.

Model convergence and fits

The predicted CPUE indices from model fit were compared to the observed CPUE and indicated a lack of fit of the two periods of sharp variations in the beginning and end of the series resulting in systematic positive residuals for Amsterdam island (Figure 6, 7). This pattern was still present for St. Paul rock lobster, but the overall fit of the abundance index was greater judging by the RMSE as a goodness-of-fit criterion (0.212, Figure 8, 9).

The visual inspection of trace plots for the key model parameters showed adequate mixing of the two chains (i.e., moving around the parameter space), which is indicative for convergence of the MCMC chains (Annex 1, 2). All key parameter MCMC chains passed both Heidelberger and Welch (Heidelberger & Welch, 1992) and Geweke (Geweke, 1992) test diagnostics further providing evidence for adequate model convergence (Table 3, 4).

Posteriors distribution

Plots of posterior densities together with prior densities are depicted in Figure 10, and 11. Summaries of posterior quantiles of parameters and quantities of management interest are

provided in Table 3 and 4. The marginal posterior for r has similar values for both Amsterdam and St. Paul rock lobster with a median of about 0.45 (0.27 - 0.62; 95% C.I.) upper than the prior for Amsterdam and 0.43 (0.26 - 0.61; 95% C.I.) for St. Paul. The posterior for K has a median of 1,452 tons (1,024 - 2,465; 95% C.I.) and 1,585 tons (1,154 - 2,642; 95% C.I.) for Amsterdam and St. Paul rock lobster respectively.

Biological reference points, phase plots and projection

The standard biological reference points were close for the two rock lobster stocks. MSY estimates was centered around 198 tons (182 - 228; 95% C.I.) and 227 tons (212 - 246; 95% C.I.) resulting in F_{MSY} median estimates of 0.36 (0.08 - 0.55; 95% C.I.) and 0.29 (0.16 - 0.67; 95% C.I.) for Amsterdam and St. Paul rock lobster respectively. B_{MSY} estimates varied from 610 tons (430 - 1,035; 95% C.I.) for Amsterdam to 665 tons (484 - 1109; 95% C.I.) for St. Paul (Table 5, 6). The B_{MSY} posterior distribution was positively skewed with a long tail of distribution.

The exploitable biomass of both rock lobster stocks has decreased until the end of the 1980s followed by an increasing trend until 2019. The harvest rate fluctuated for much above F_{MSY} over the period 1981-1988 followed by an overall decrease trend below of F_{MSY} since the end of the 1990s (Figure 12, 13).

Models indicated that Amsterdam rock lobster was no overfished² ($B > B_{MSY}$) and was no subject to overfishing³ ($F < F_{MSY}$). The current biomass state B_{2019} over B_{MSY} was 53% above B_{MSY} (1.09 - 2.01; 95% C.I.) and the current fishing mortality F_{2019} over F_{MSY} is 50% below F_{MSY} (0.38 - 0.66; 95% C.I.). The situation was less evident for St. Paul rock lobster with a current biomass state 24% above B_{MSY} (0.98 - 1.61; 95% C.I.) and the current fishing mortality was 26% below F_{MSY} (0.57 - 0.93, 95% C.I.).

Kobe phase plots showed that the rock lobster stocks appear to be no overfished ($B > B_{MSY}$) and no overfishing is occurring (green phase $F < F_{MSY}$) except in the beginning of the 1980s (Figure 14, 15).

Projections based on a range of alternative constant TAC for the period 2020-2029 showed that the current exploitation levels are consistent with the MSY management objective (Figure 16, 17).

² Overfished refers to the state of a stock upon which overfishing has occurred. The stock is no longer able to produce at a maximum sustainable yield.

³ Overfished refers to the state of a stock upon which overfishing has occurred. The stock is no longer able to produce at a maximum sustainable yield.

Sensitivity analysis

All scenarios produce similar trends in relative stock status B/B_{MSY} and F/F_{MSY} for both rock lobster stocks (Figure 18, 19, 20, 21). However, absolute stock status and parameter estimates were sensitive to the choice of the shape parameter (m , B_{MSY}/K) of the Pella-Tomlinson surplus production (Figure 22, 23, 24, 25).

Kobe phase plots were similar among all scenarios indicated that the rock lobster stocks were not overfished and not subjected to overfishing with 94% probability for both stocks (Figure 26, 27).

5. Discussion

The results of the first assessment of St. Paul and Amsterdam rock lobster suggest that the two stocks biomass have experienced a period of sharply declined following by a period of steady increase. The analysis shows that the 2019 status of both rock lobster stocks is likely above B_{MSY} and that fishing mortality is below F_{MSY} .

However, it is important to highlight that there is uncertainty in estimated quantities of stock biomass as well as the estimated harvest rates, since that 95% credibility intervals are somewhat high.

Larger indices and variability observed at the beginning and the end of the observed standardized CPUEs time-series were poorly fitted by the model. Several explanations for the poor fit to the complete data set could be raised including the assumption of a linear relationship between the CPUE and abundance is invalid, the oversimplification of the surplus production models which do not consider changes in the size, age or sex structure of the population.

Sensitivity analysis for alternative structural models and biological which includes different B_{MSY}/K shows that the reference points B/B_{MSY} and F/F_{MSY} estimates were fairly robust to the choice of B_{MSY}/K . Furthermore, varying intrinsic growth rates suggests that high resilience for St. Paul and Amsterdam might be the best hypothesis given the abundance index data.

6. Acknowledgments

This work was conducted using data collected from the rock lobster fishery observer program (COPEC) supported by the Museum National d'Histoire Naturelle (MNHN) and funded by the French Southern Territories (TAAF). The author wishes to thank all fishery observers who collected data onboard fishing vessels, the Museum national d'Histoire naturelle team in charge

of the scientific assessment of the French southern fisheries Guy Duhamel, Patrice Pruvost, Clara Péron, Charlotte Chazeau, Nicolas Gasco, Alexis Martin and especially Félix Massiot-Granier for his support conducting Bayesian analysis.

7. Tables

Table 1: Summary of prior for the reference case Bayesian state-space surplus production model for St. Paul and Amsterdam rock lobster.

Parameter	Description	Prior
K	Carrying capacity (t)	Lognormal-range(500, 10000)
r	Intrinsic rate of population increase	Lognormal-range(0.1, 1)
q	Catchability	Inverse-gamma(0.001, 0.001)
B_{MSY}/K	Biomass at MSY relative to the carrying capacity	0.42
φ	Initial rate of biomass depletion	Lognormal(0.6,0.5)
σ_{η}^2	Process variance	Inverse-gamma(0.001, 0.001)
σ_{ϵ}^2	Observation variance	Inverse-gamma(0.001, 0.001)

Table 2: Summary of uncertainty grid model specifications for St. Paul and Amsterdam rock lobster.

Scenario	Description	BMSY/K	r prior
Reference	Reference model	0.42	Lognormal-range(0.1, 1)
1	Pella-Tomlinson model with low resilience r hypothesis	0.42	Lognormal(0.3, 0.3)
2	Pella-Tomlinson model with high resilience r hypothesis	0.42	Lognormal(0.6, 3)
3	Fox model with uninformative r prior	0.37	Lognormal-range(0.1, 1)
4	Fox model with low resilience r hypothesis	0.37	Lognormal(0.3, 0.3)
5	Fox model with high resilience r hypothesis	0.37	Lognormal(0.6, 3)
6	Schaefer model with uninformative r prior	0.5	Lognormal-range(0.1, 1)
7	Schaefer model with low resilience r hypothesis	0.5	Lognormal(0.3, 0.3)
8	Schaefer model with high resilience r hypothesis	0.5	Lognormal(0.6, 3)

Table 3: Summary of posteriors quantiles indicating the median and the 95% credible interval and the Geweke and Heidel p-value of the convergence diagnostics for the reference case model for Amsterdam rock lobster.

	Median	LCI	UCI	Geweke.p	Heidel.p
K	1452.75	1024.196	2465.734	0.213	0.219
r	0.428	0.256	0.606	0.204	0.371
q	12.36×10^{-6}	7.515×10^{-6}	17.86×10^{-6}	0.459	0.355
φ	0.671	0.412	0.97	0.793	0.519
σ_{η}^2	0.005	0.001	0.019	0.575	0.820
σ_{ϵ}^2	0.027	0.008	0.055	0.855	0.634

Table 4: Summary of posteriors quantiles indicating the median and the 95% credible interval and the Geweke and Heidel p-value of the convergence diagnostics for the reference case model for St. Paul rock lobster.

	Median	LCI	UCI	Geweke.p	Heidel.p
K	1585.093	1154.162	2642.892	0.428	0.261
r	0.451	0.273	0.62	0.737	0.415
q	14.44×10^{-6}	8.558×10^{-6}	20.25×10^{-6}	0.435	0.419
φ	0.567	0.394	0.825	0.846	0.842
σ_y^2	0.003	0.001	0.009	0.254	0.075
σ_ϵ^2	0.02	0.01	0.039	0.528	0.440

Table 5: Summary of posteriors quantiles of reference points indicating the median and the 95% credible interval for the reference case model for Amsterdam rock lobster. B/B_{MSY} and F/F_{MSY} are presented for the final assessment year.

	Median	LCI	UCI
F_{MSY}	0.32	0.19	0.46
B_{MSY}	610.09	430.12	1035.51
MSY	198.15	181.98	228.40
B/B_{MSY}	1.53	1.09	2.01
F/F_{MSY}	0.50	0.38	0.66

Table 6: Summary of posteriors quantiles of reference points indicating the median and the 95% credible interval for the reference case model for St. Paul rock lobster. B/B_{MSY} and F/F_{MSY} are presented for the final assessment year.

	Median	LCI	UCI
F_{MSY}	0.34	0.21	0.47
B_{MSY}	665.67	484.70	1109.91
MSY	227.23	212.61	246.37
B/B_{MSY}	1.24	0.98	1.61
F/F_{MSY}	0.74	0.57	0.93

Table 7: Summary of model diagnostics for the different sensitivity analysis scenarios for Amsterdam rock lobster. Nobs, Parameters, DF, RMSE and DIC stands for number of observations, number of parameters, degree of freedom, root mean squared error and deviance information criterion respectively.

	Reference	1	2	3	4	5	6	7	8
Nobs	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Parameters	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
DF	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0
RMSE	17.2	16.8	16.9	16.9	17.0	16.9	17.4	17.1	16.8
DIC	-9.2	13.4	-12.8	-21.1	-22.1	-6.5	20.7	31.3	4.6

Table 8: Summary of model diagnostics for the different sensitivity analysis scenarios for St. Paul rock lobster. Nobs, Parameters, DF, RMSE and DIC stands for number of observations, number of parameters, degree of freedom, root mean squared error and deviance information criterion respectively.

	Reference	1	2	3	4	5	6	7	8
Nobs	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Parameters	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
DF	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0
RMSE	15.1	15.2	15.1	15.1	15.1	15.1	15.3	15.1	15.3
DIC	-49.1	-45.5	-48.2	-48.9	-49.2	-48.1	-45.5	-32.0	-44.1

8. Figures

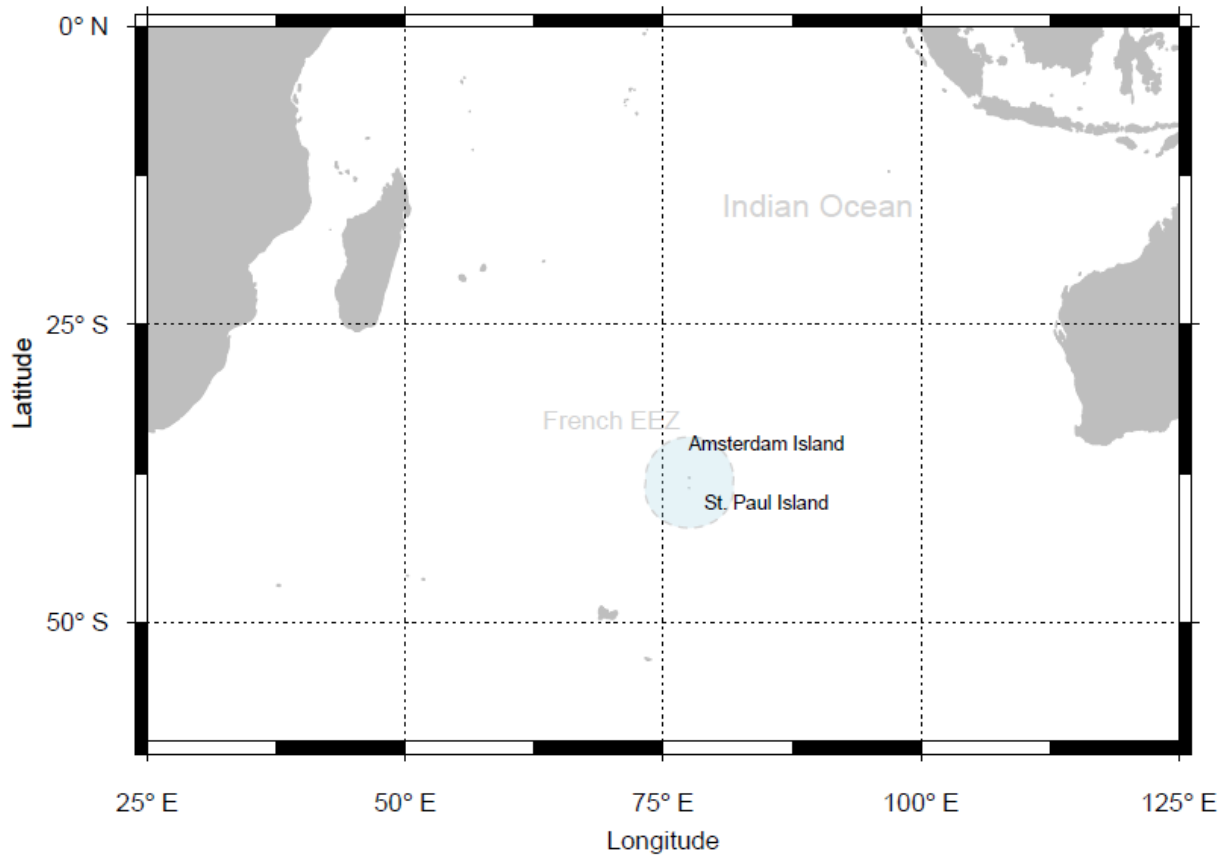


Figure 1: Location of Saint Paul and Amsterdam within the French EEZ in the South Indian Ocean. The French EEZ is delineated by a grey dashed line.

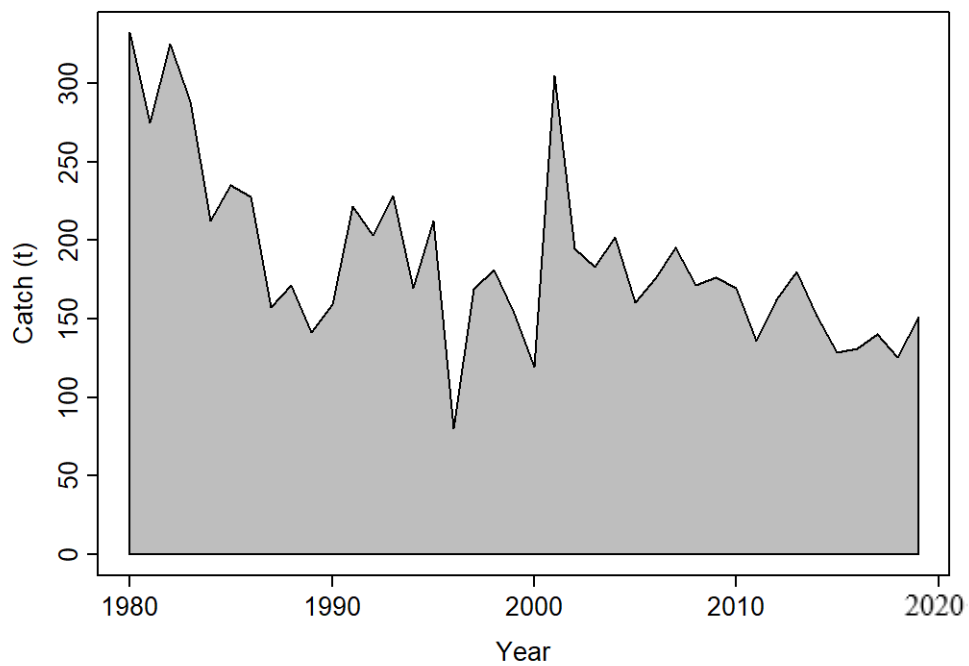


Figure 2: Time-series of catch in metric tons (t) for Amsterdam rock lobster.

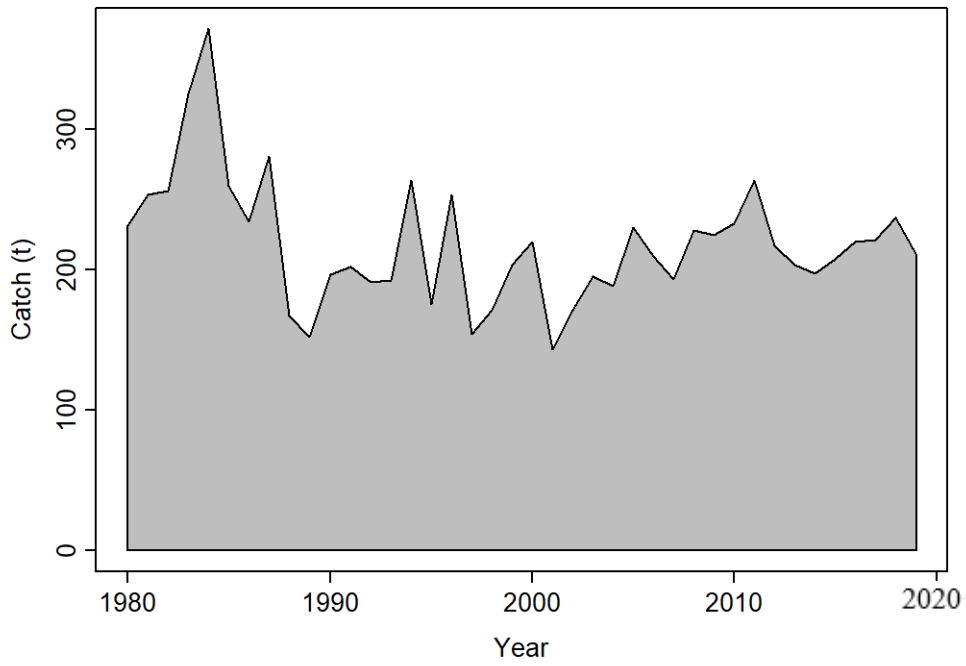


Figure 3: Time-series of catch in metric tons (t) for St. Paul rock lobster.

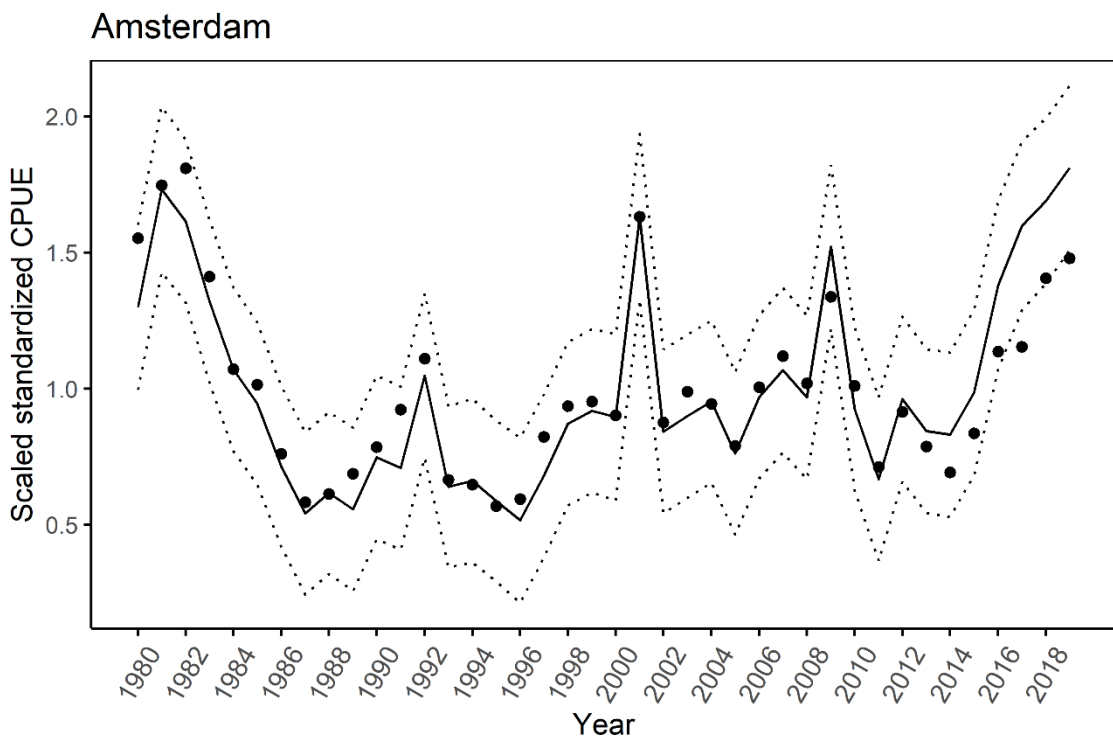


Figure 4: Comparative plot of the relative nominal CPUE (red) and GLM standardised CPUE series (black) for Amsterdam with the 95% credible interval (dashed lines).

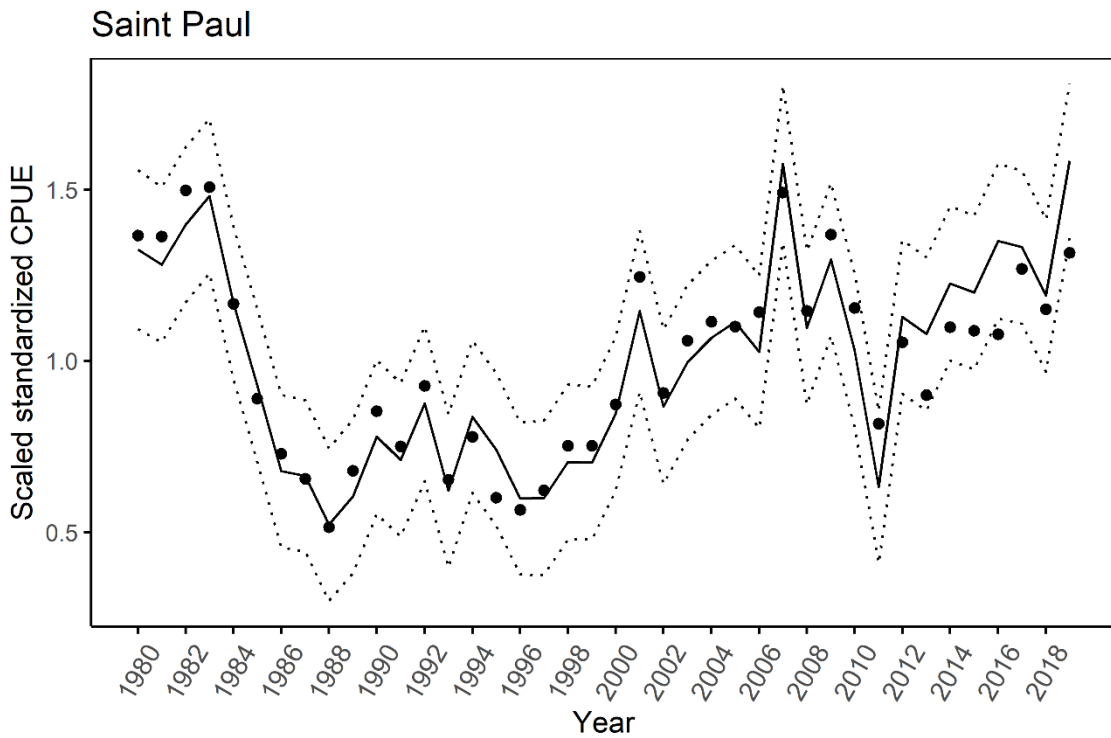


Figure 5: Comparative plot of the relative nominal CPUE (red) and GLM standardised CPUE series (black) for St. Paul with the 95% credible interval (dashed lines).

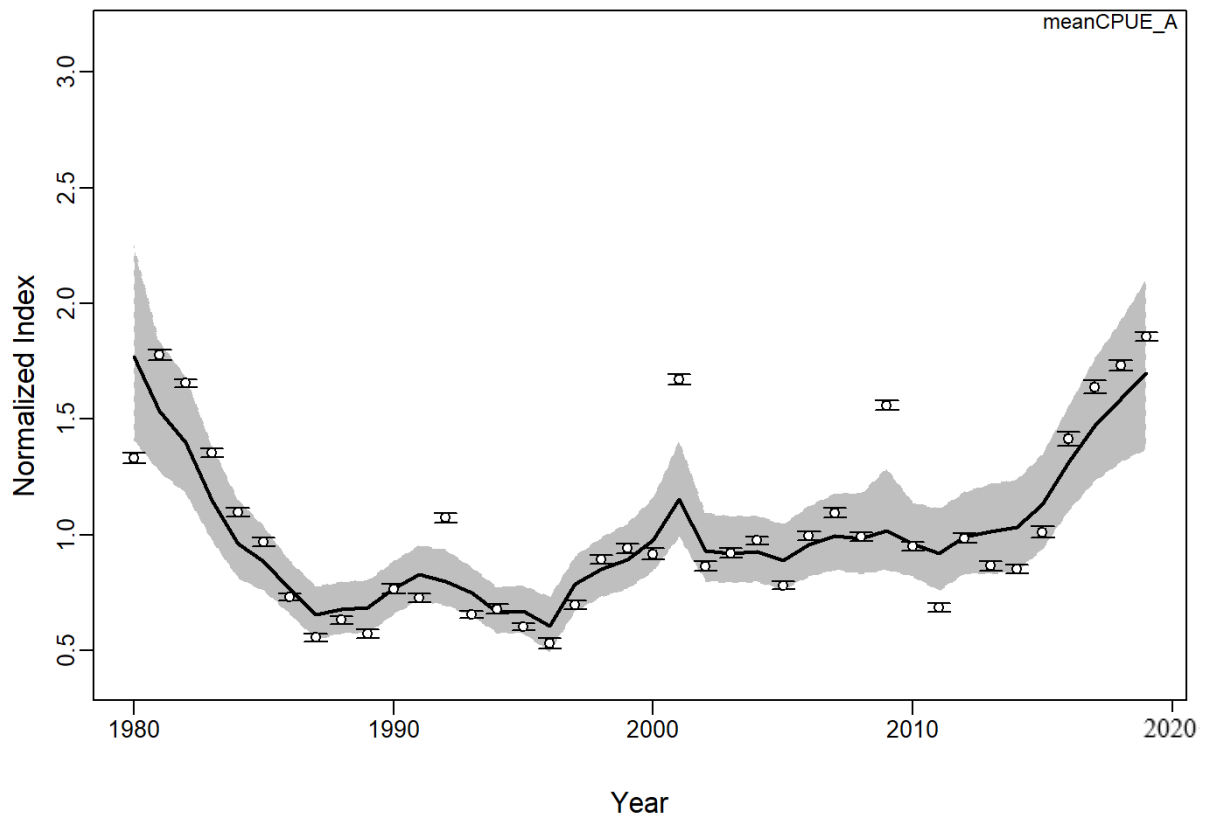


Figure 6: Time-series of observed (circle) and predicted (solid line) catch per unit effort (CPUE) of the Amsterdam rock lobster for the Bayesian state-space surplus production model. Shaded area indicates the 95% credible interval.

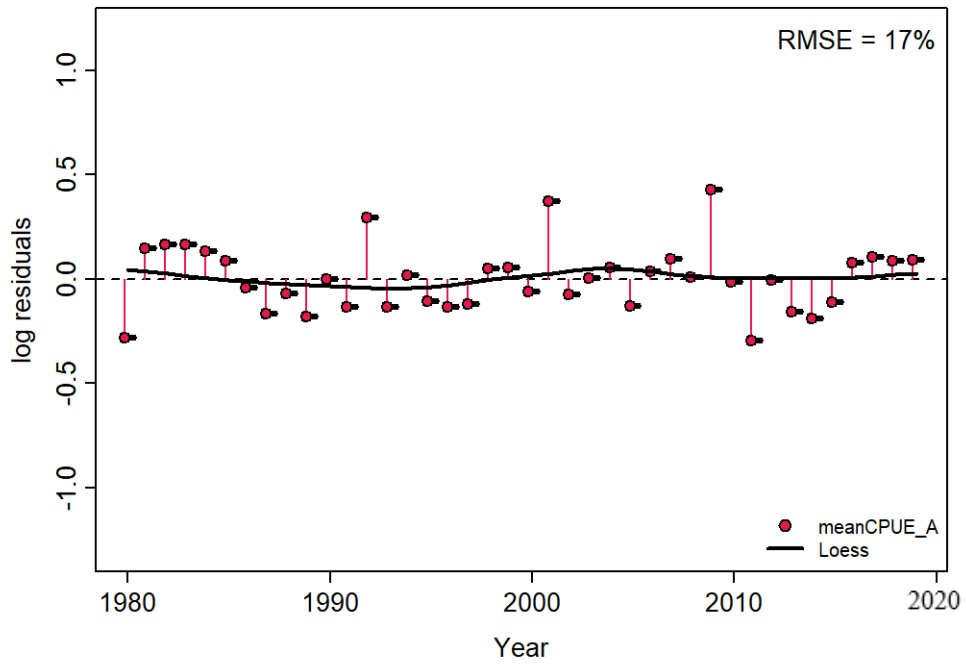


Figure 7: Residual diagnostic plots for the reference case model for Amsterdam rock lobster. The solid black line indicates a loess smoother through all residuals.

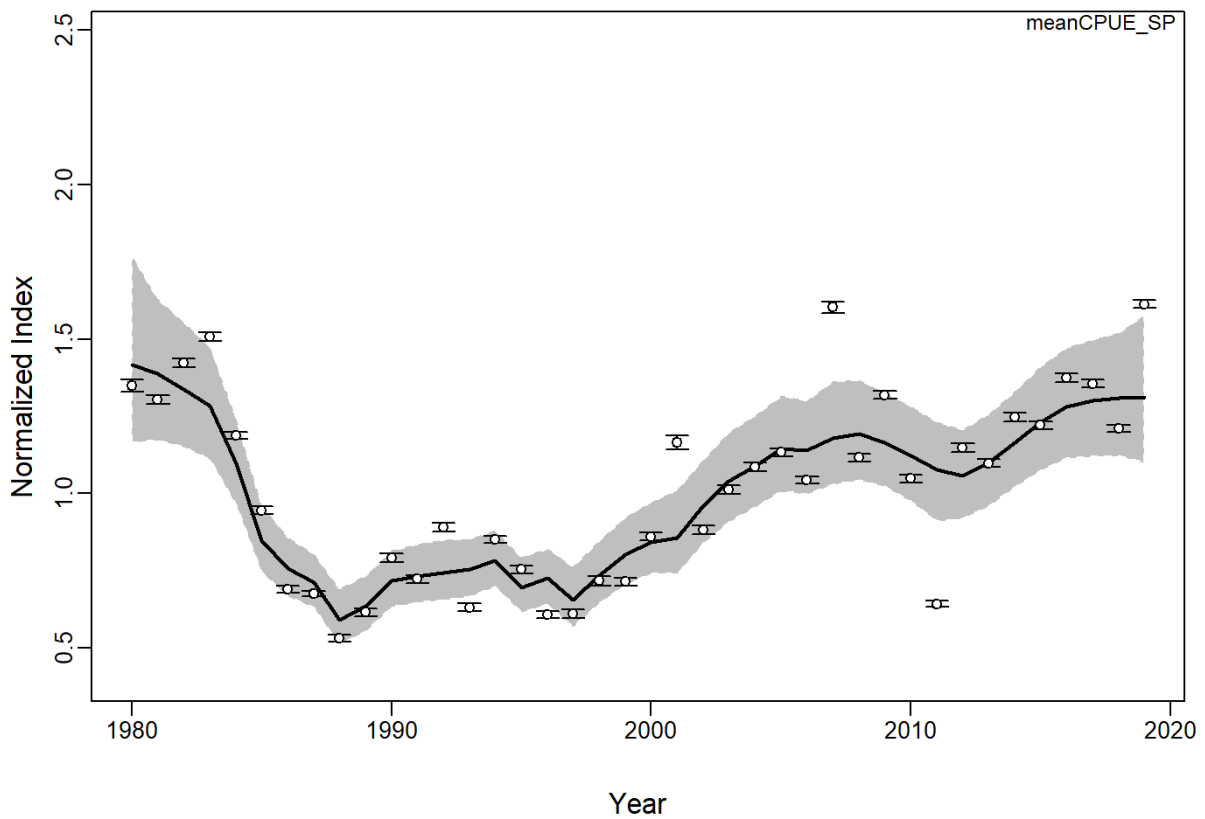


Figure 8: Time-series of observed (circle) and predicted (solid line) catch per unit effort (CPUE) of the St Paul rock lobster for the Bayesian state-space surplus production model. Shaded area indicates the 95% credible interval.

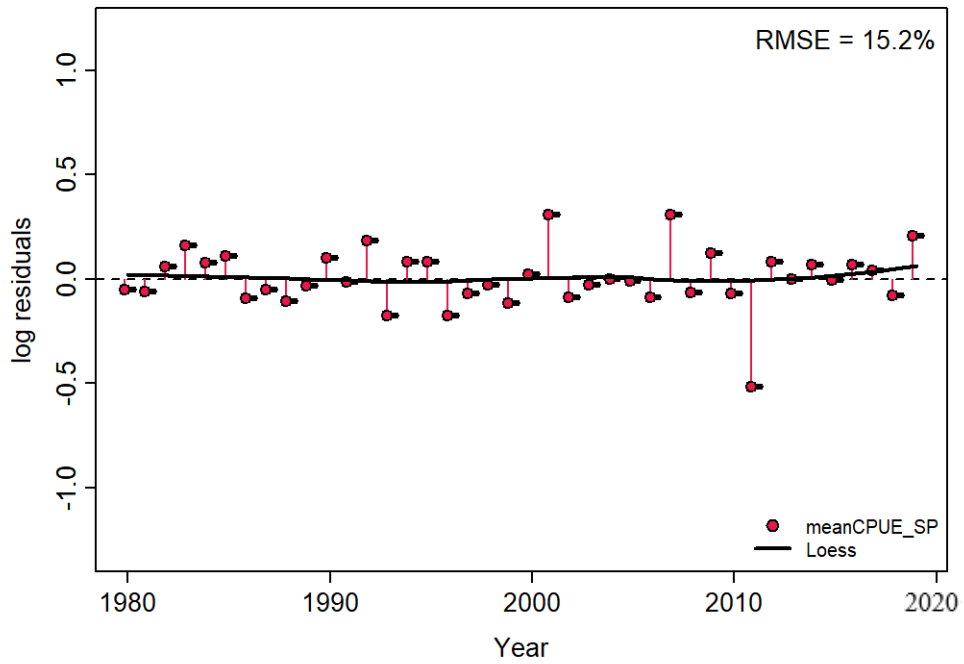


Figure 9: Residual diagnostic plots for the reference case model for St. Paul rock lobster. The solid black line indicates a loess smoother through all residuals.

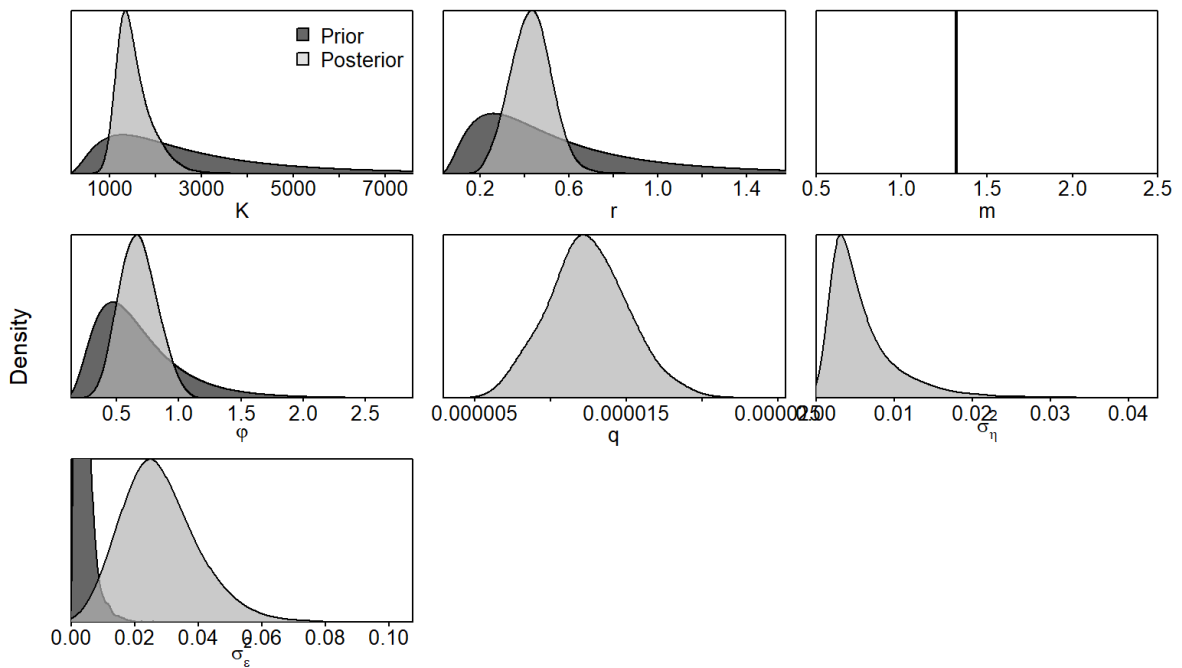


Figure 10: Prior and posterior distributions for the reference case model for Amsterdam rock lobster. Posteriors distributions are plotted using kernel densities estimates (black lines).

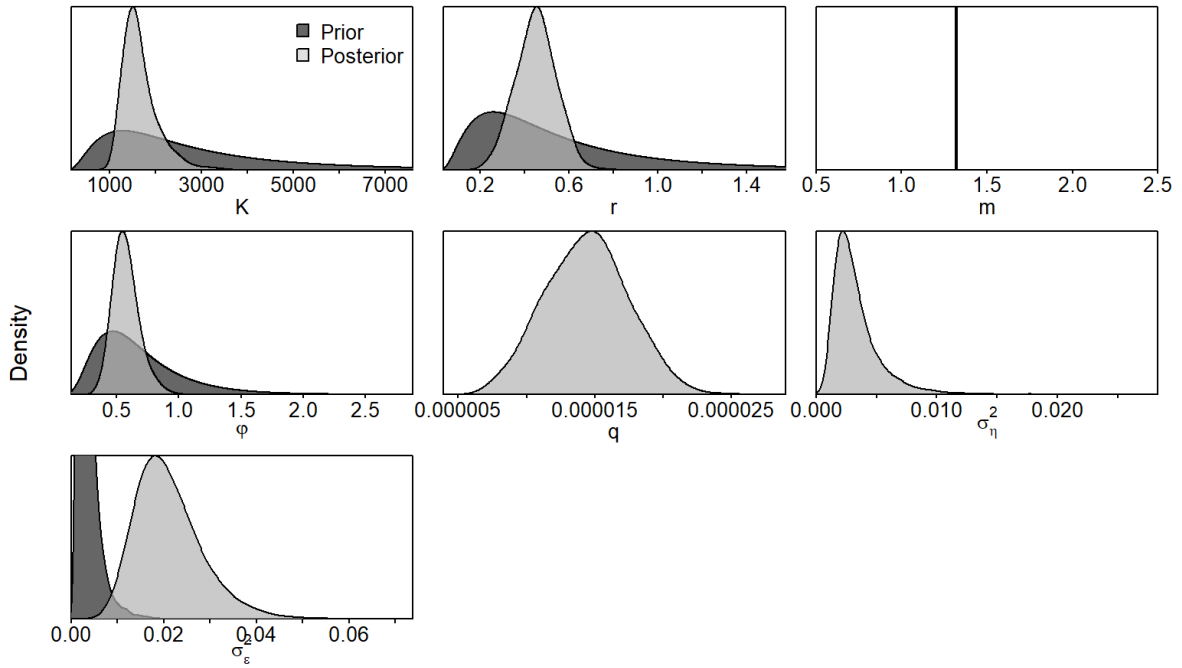


Figure 11: Prior and posterior distributions of the reference case model for St. Paul rock lobster. Posteriors distributions are plotted using kernel densities estimates (black lines).

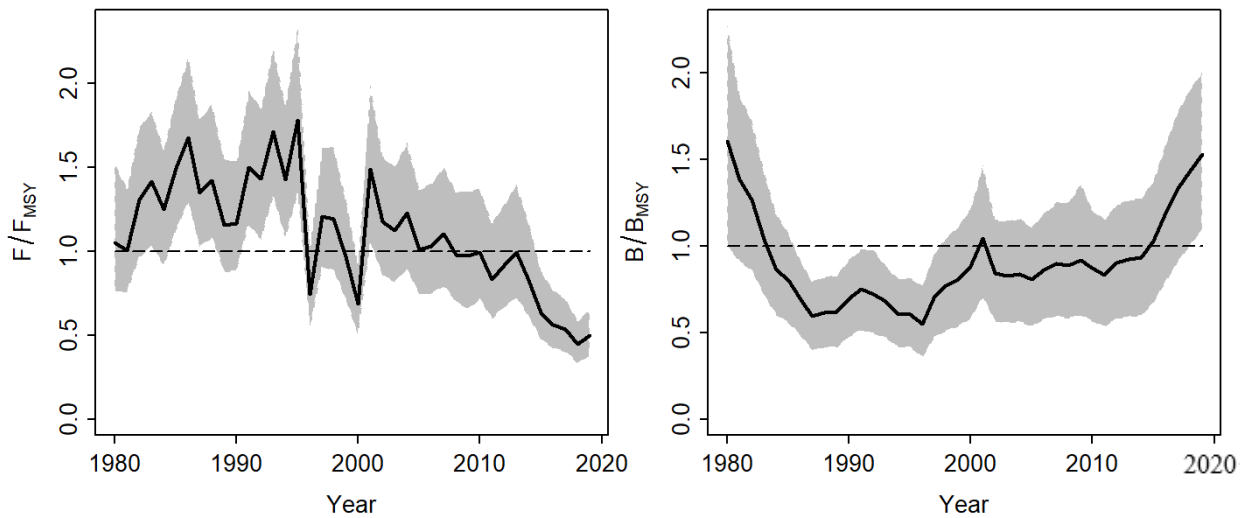


Figure 12: Trends in harvest rate relative to FMSY and biomass relative to BMSY for the reference case model for Amsterdam rock lobster. Shaded grey area indicates the 95% credible intervals.

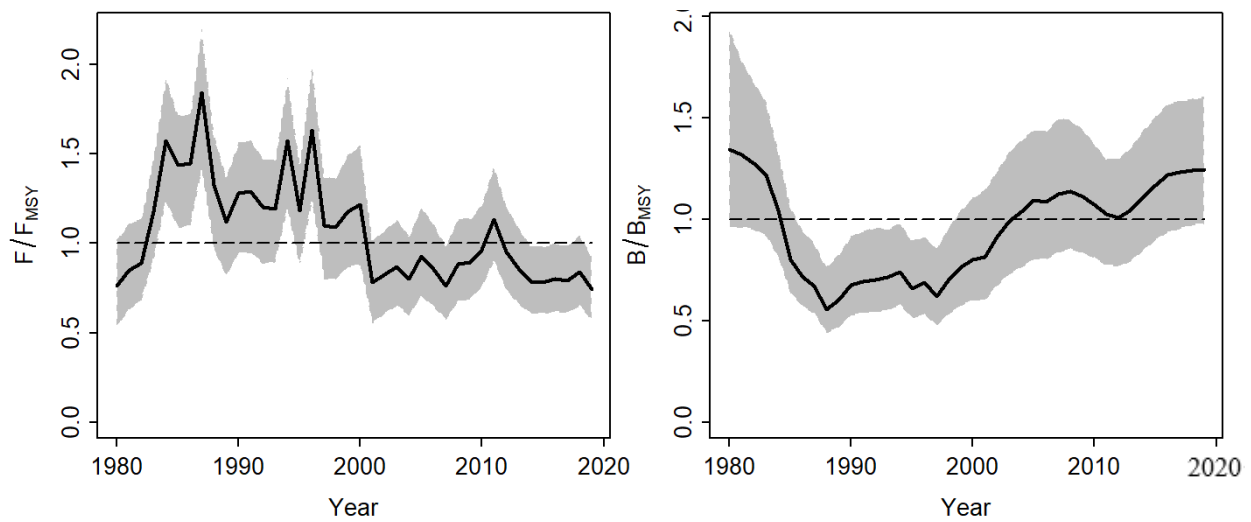


Figure 13: Trends in harvest rate relative to FMSY and biomass relative to BMSY for the reference case model for St. Paul rock lobster. Shaded grey area indicates 95% credible interval.

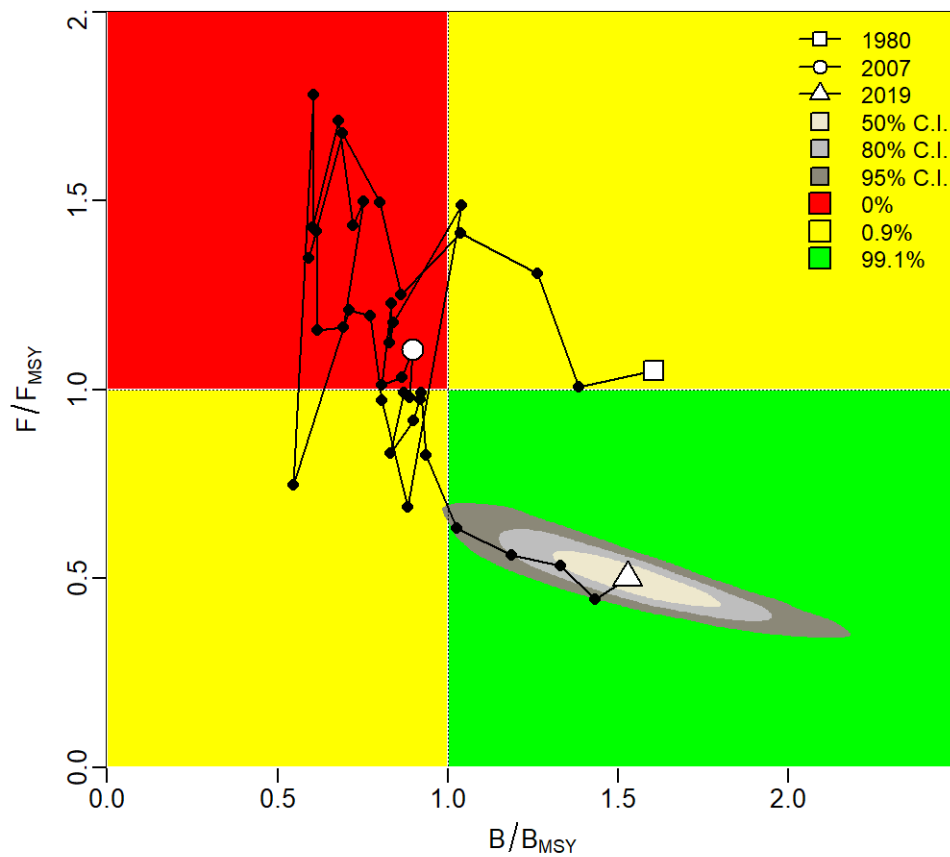


Figure 14: Kobe phase plot showing estimated trajectories (1980-2019) of B/B_{MSY} and F/F_{MSY} for the reference case mode for Amsterdam rock lobster. Different grey shaded areas denote the 50, 80 and 95 % credible interval for the terminal assessment year. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

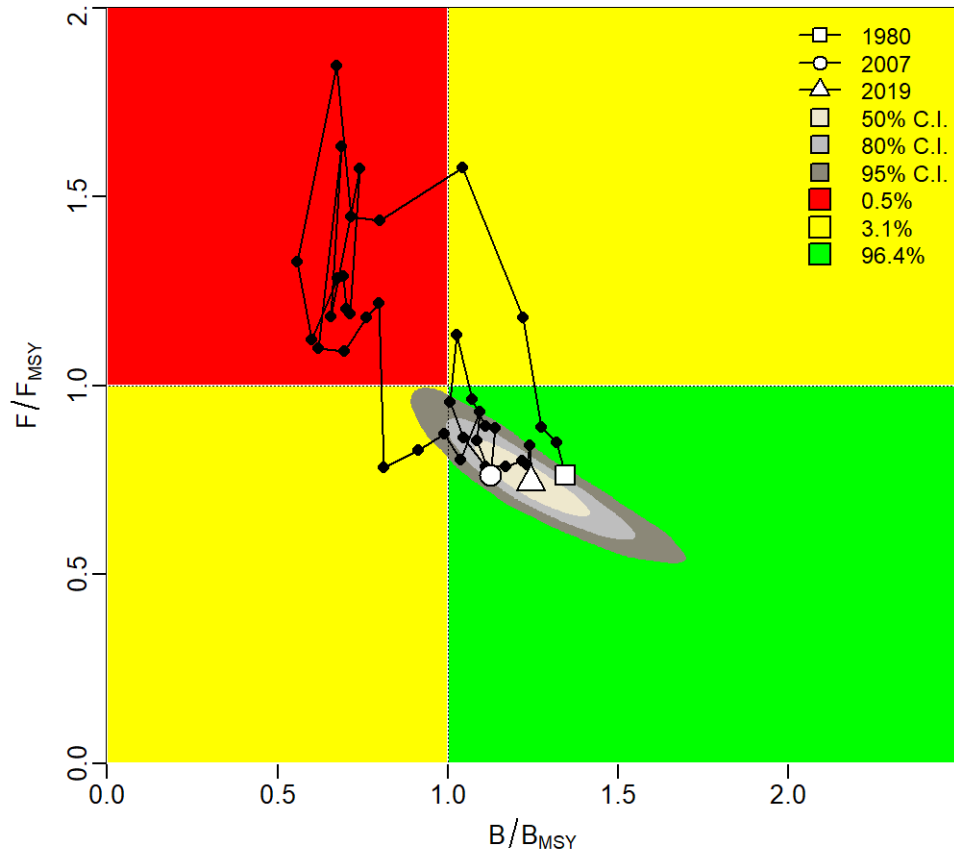


Figure 15: Kobe phase plot showing estimated trajectories (1980-2019) of B/B_{MSY} and F/F_{MSY} for the reference case model for St. Paul rock lobster. Different grey shaded areas denote the 50, 80 and 95% credible interval for the terminal assessment year. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

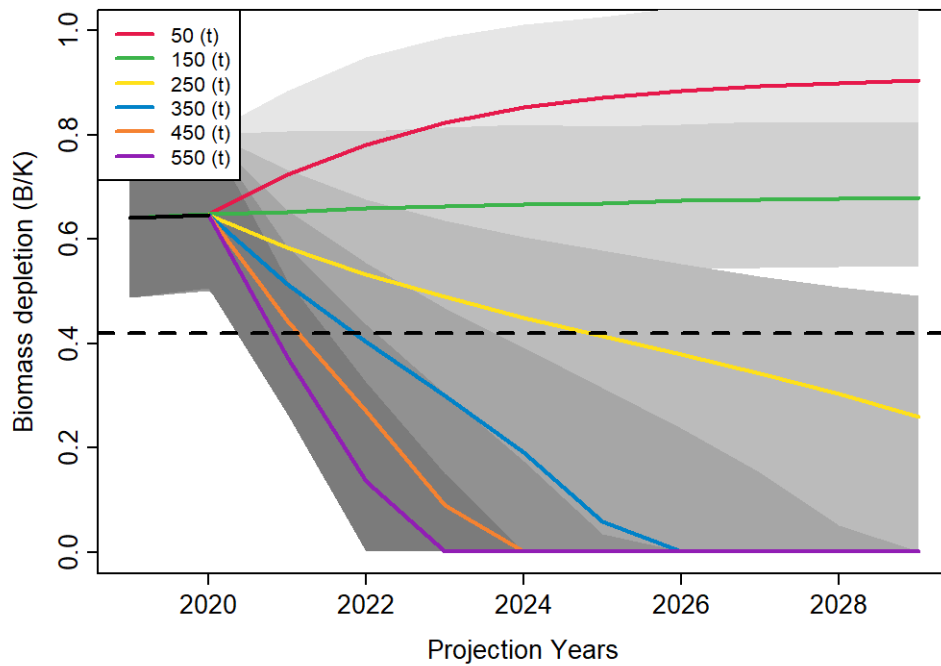


Figure 16: Projections (2020-2029) based on the reference case model over a sequence of future TAC from 50 to 550 tons for Amsterdam rock lobster. The initial catch for the years 2020-2021 was set to the 2020 TAC. The dashed line denotes BMSY.

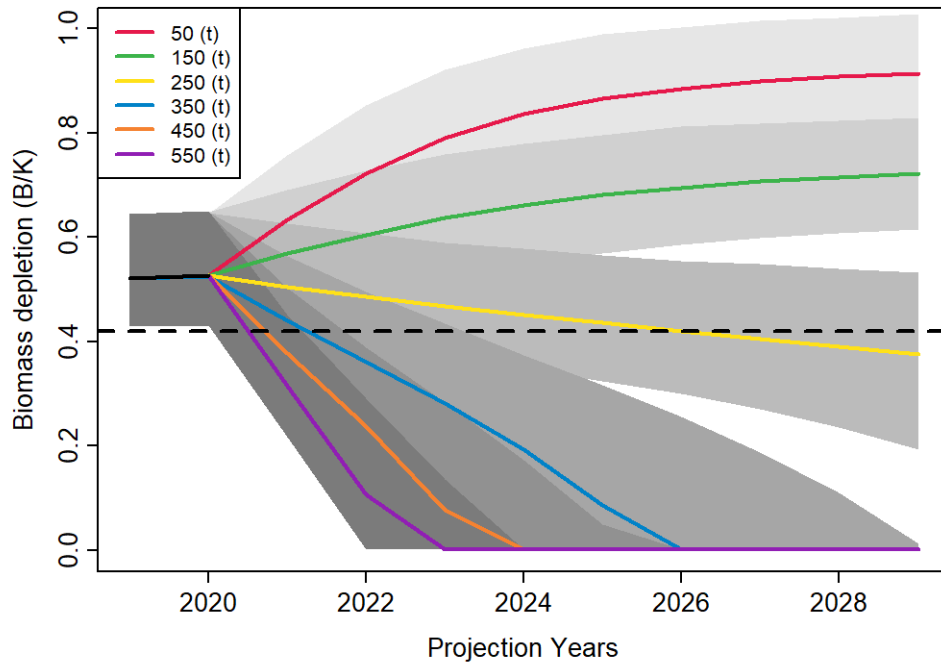


Figure 17: Projections (2020–2029) based on the reference case model over a sequence of future TAC from 50 to 550 tons. The initial catch for the years 2020–2021 was set to the 2019 TAC. The dashed line denotes BMSY.

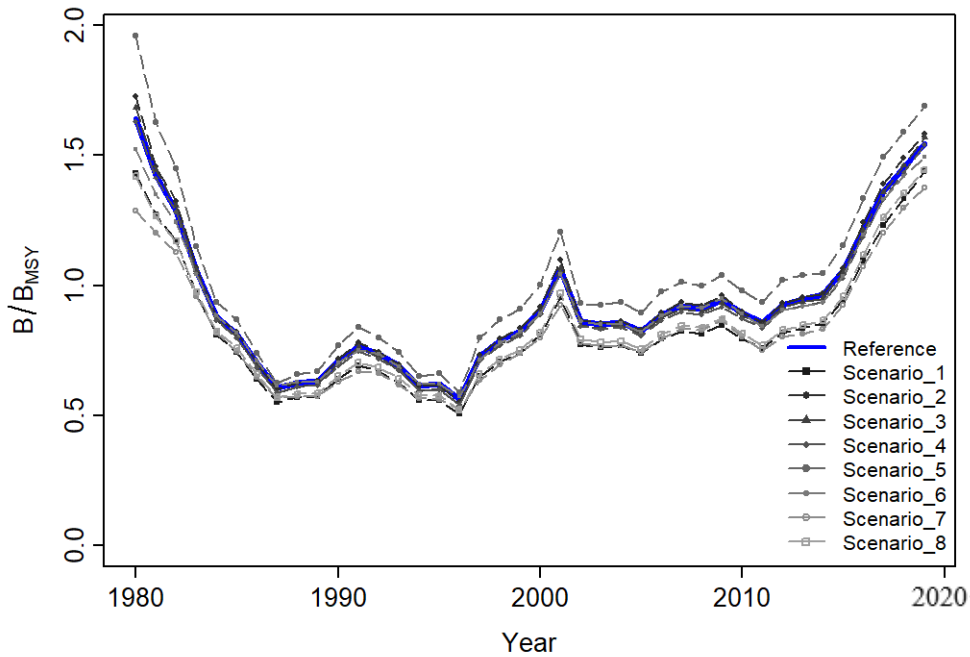


Figure 18: Time series of B/B_{msy} for the different sensitivity analysis scenarios for Amsterdam rock lobster.

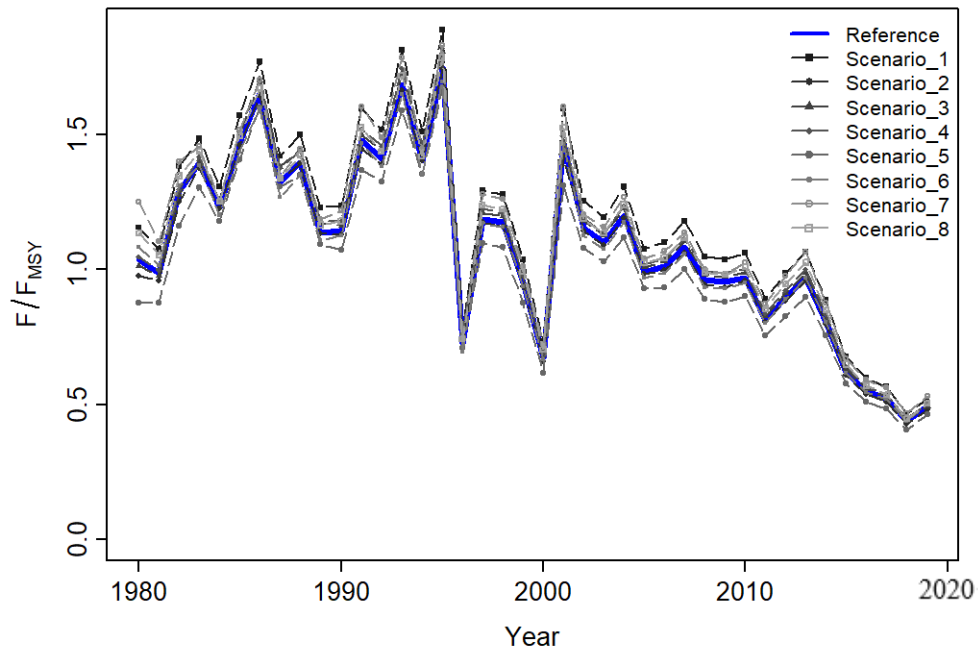


Figure 19: Time series of F/F_{MSY} for the different sensitivity analysis scenarios for Amsterdam rock lobster.

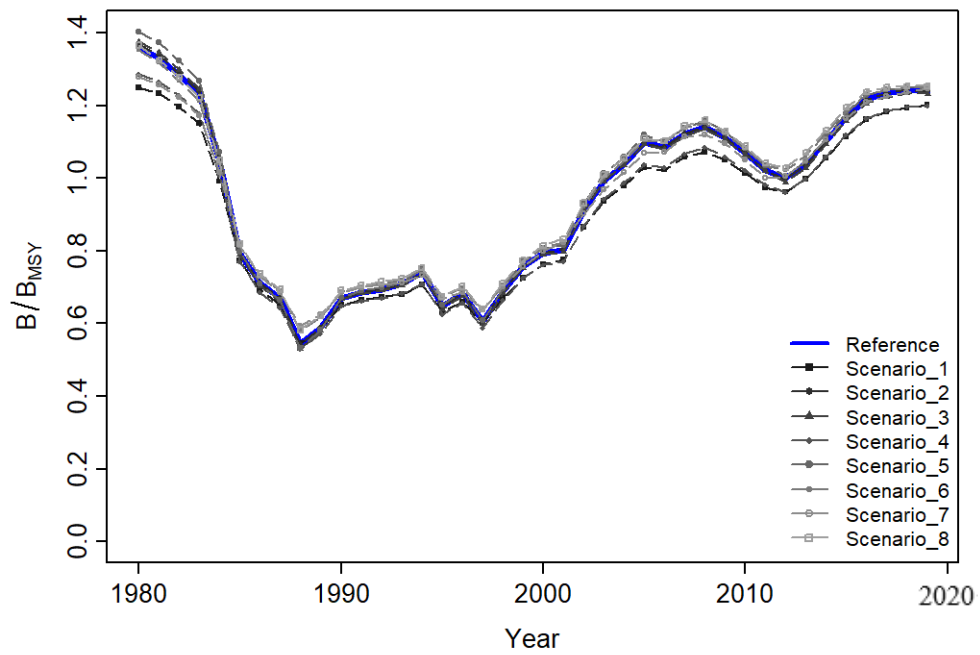


Figure 20: Time series of B/B_{MSY} for the different sensitivity analysis scenarios for St. Paul rock lobster.

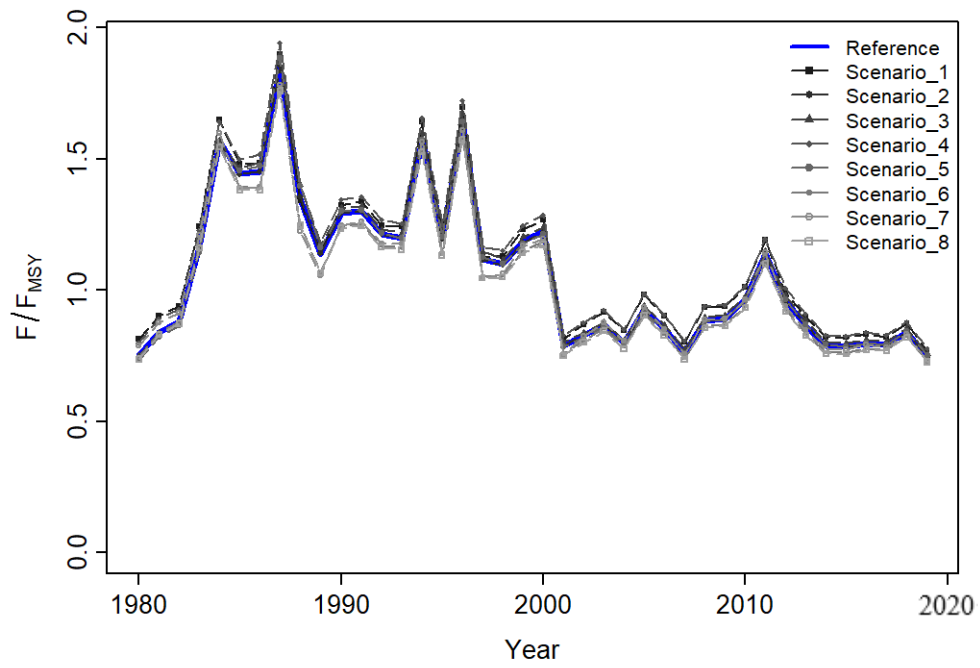


Figure 21: Time series of F/F_{MSY} for the different sensitivity analysis scenarios for St. Paul rock lobster.

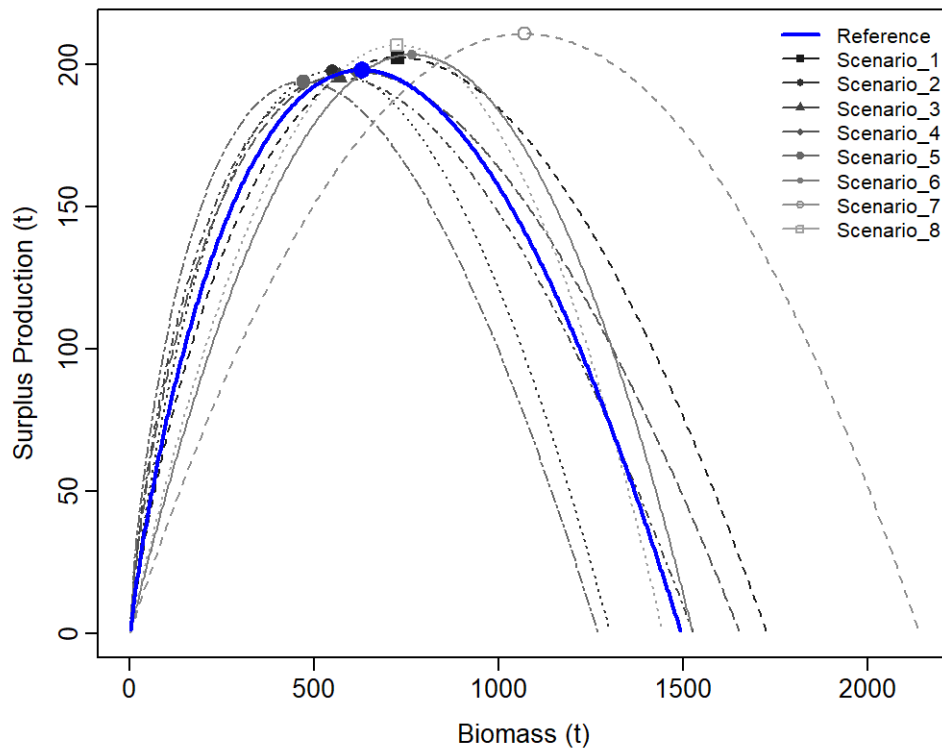


Figure 22: Surplus Production functions for the different sensitivity analysis scenarios for Amsterdam rock lobster.

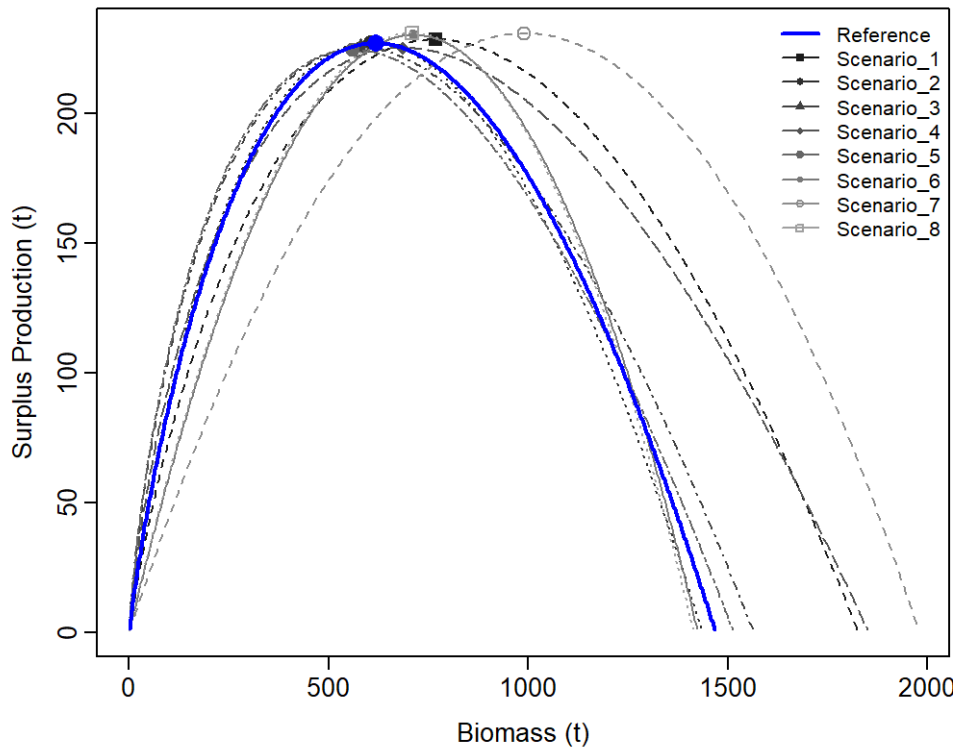


Figure 23: Surplus Production functions for St. Paul rock lobster.

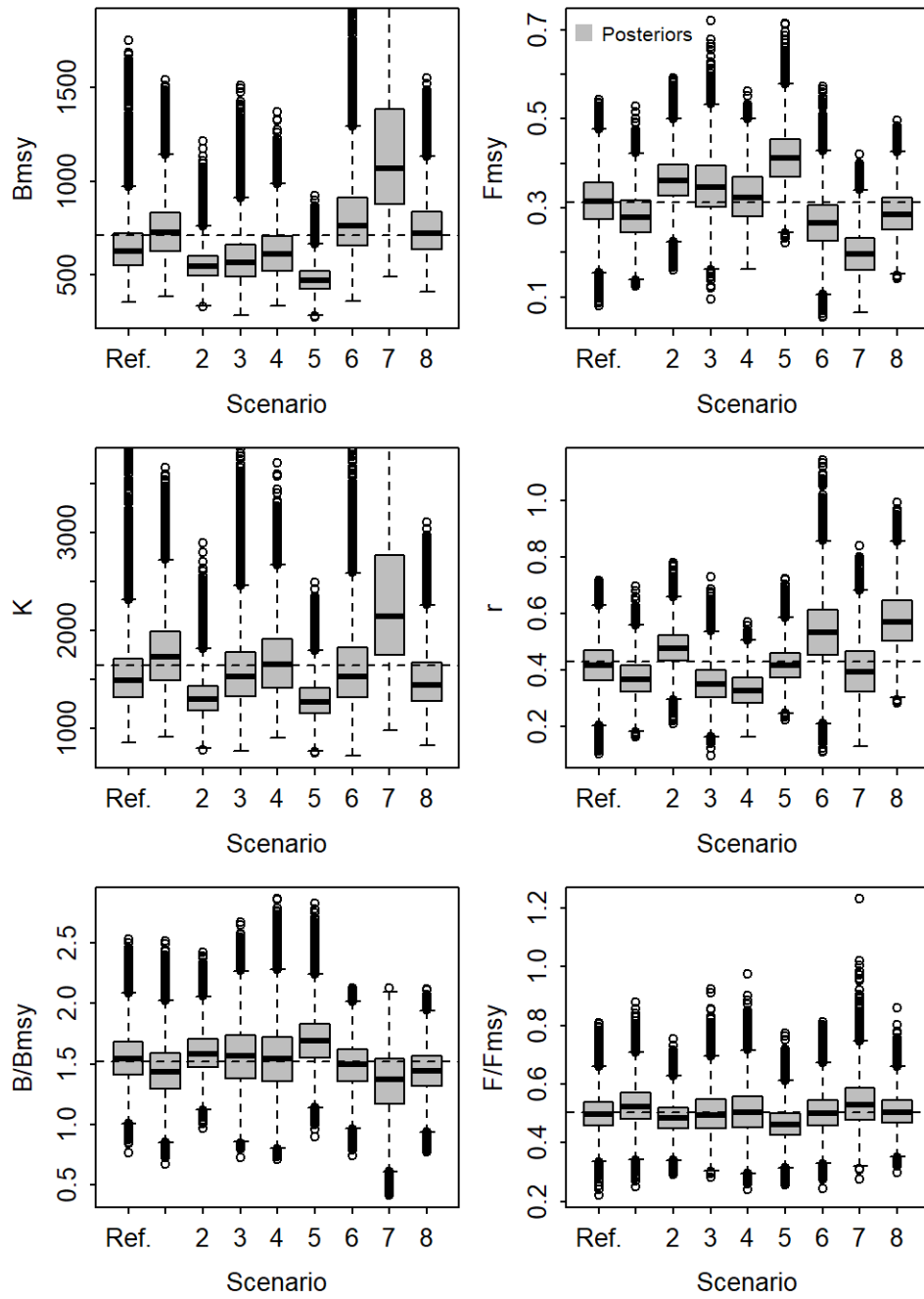


Figure 24: Boxplots of the posteriors distributions for the different sensitivity analysis scenarios for Amsterdam rock lobster where B/B_{MSY} and F/F_{MSY} are presented for the final assessment year. Dashed lines denote means across all of the scenarios.

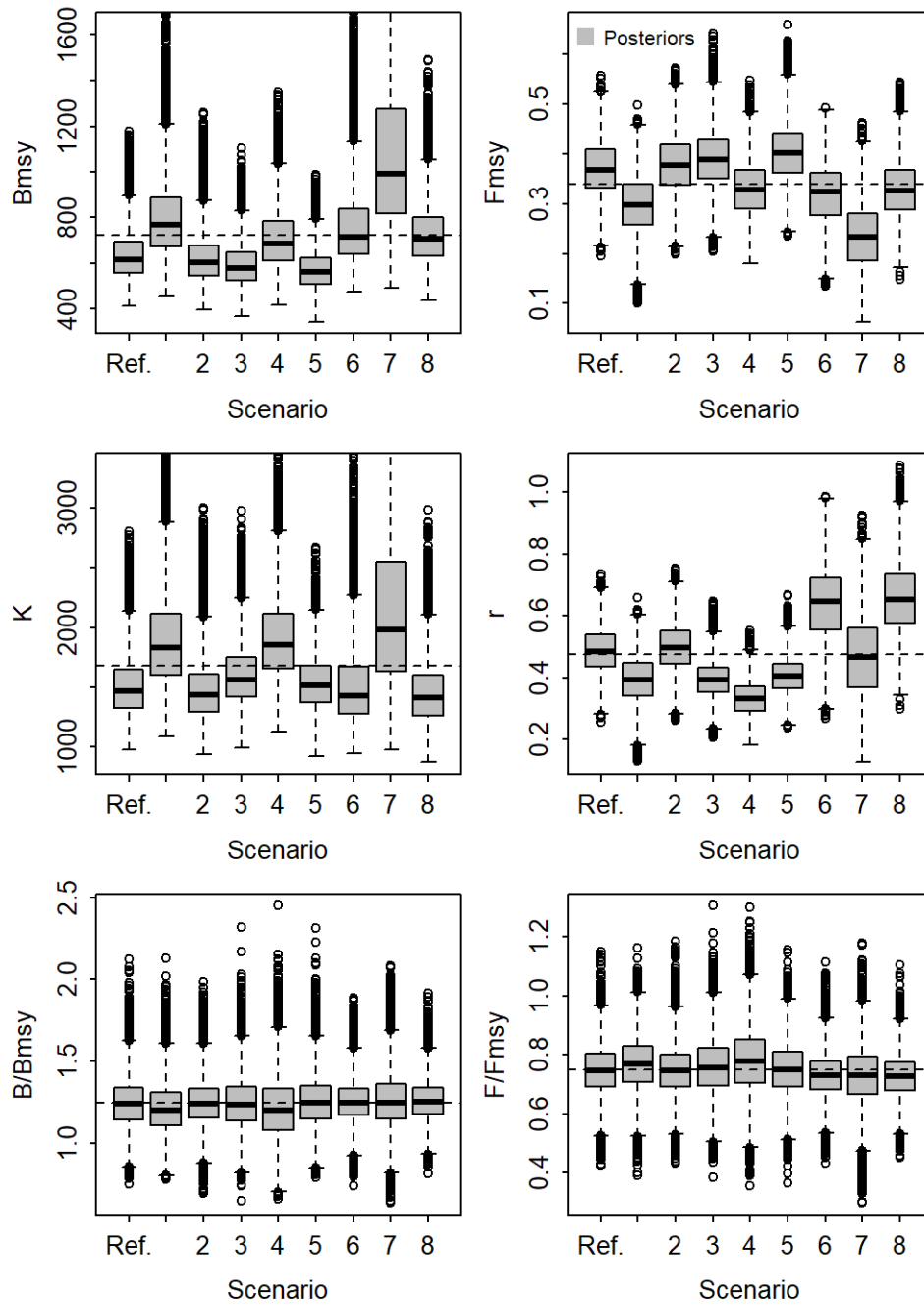


Figure 25: Boxplots of the posteriors distributions for the different sensitivity analysis scenarios for St. Paul rock lobster where B/B_{MSY} and F/F_{MSY} are presented for the final assessment year. Dashed lines denote means across all of the scenarios.

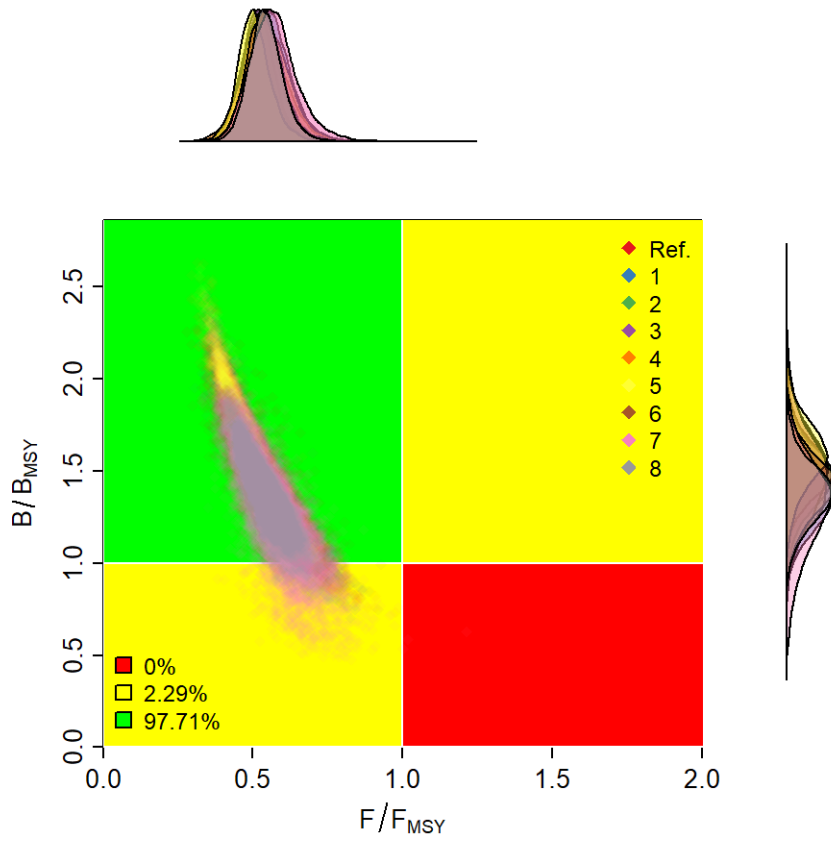


Figure 26: Kobe phase plot showing estimated terminal B/B_{MSY} and F/F_{MSY} for different sensitivity analysis scenarios for Amsterdam rock lobster. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

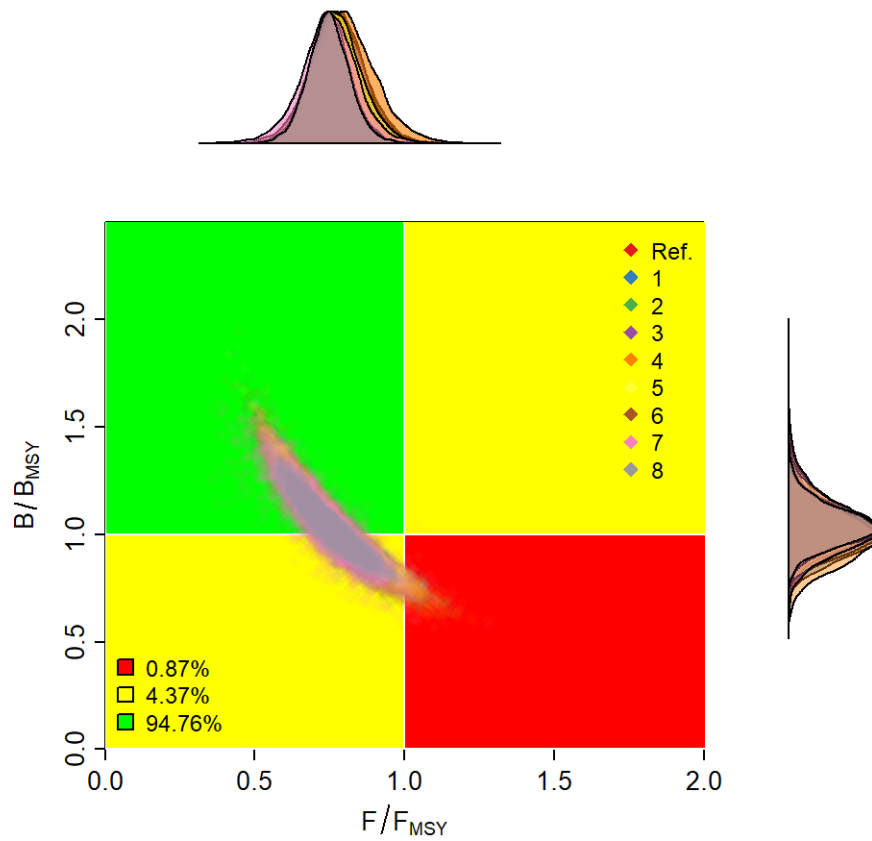


Figure 27: Kobe phase plot showing estimated terminal B/B_{MSY} and F/F_{MSY} for different sensitivity analysis scenarios for St. Paul rock lobster. The probability of terminal year points falling within each quadrant is indicated in the figure legend.

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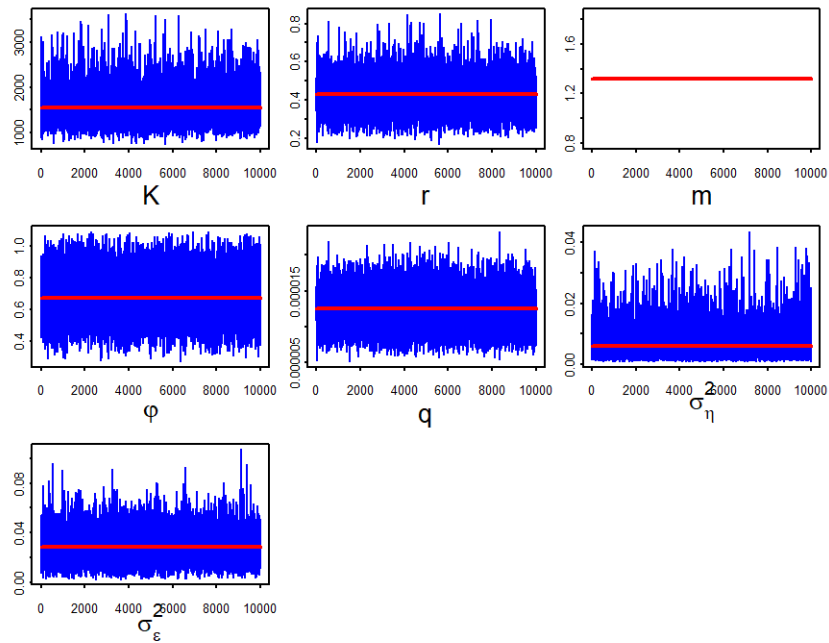
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10. Annexes

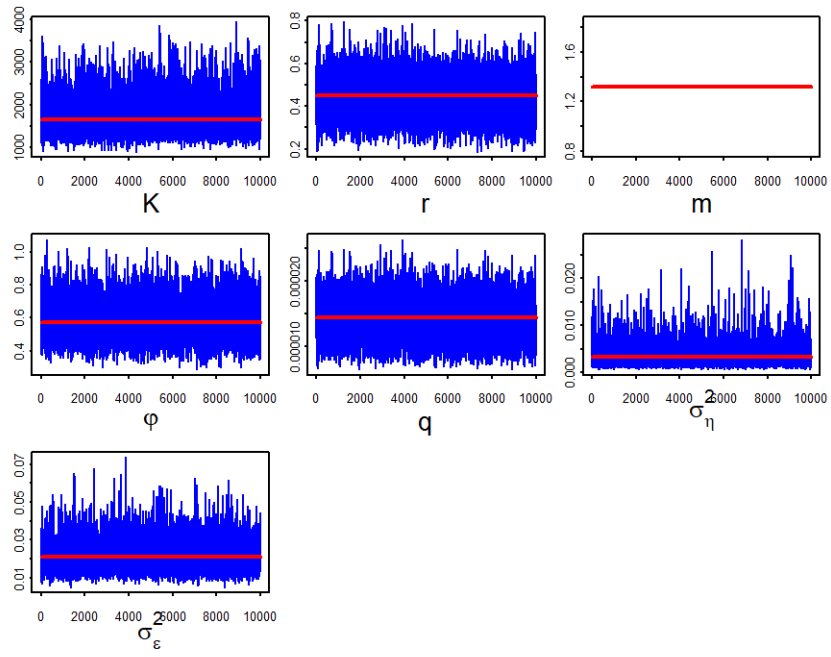
Annex 1

Annex 1: Trace plots for the reference case model parameter drawn from MCMC samples in the Bayesian state-surplus production model for Amsterdam rock lobster.



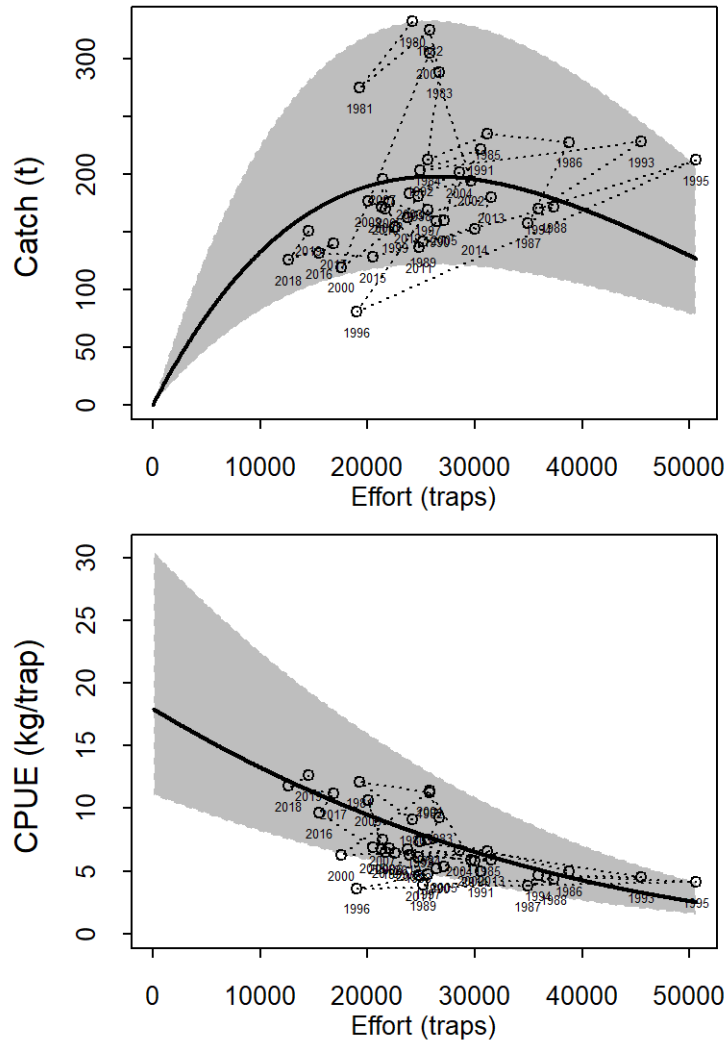
Annex 2

Annex 2: Trace plots for the reference case model parameter drawn from MCMC samples in the Bayesian state-surplus production model for St. Paul rock lobster.



Annex 3

Annex 3: Equilibrium yield (t) and CPUE (kg/trap) for the reference case model for Amsterdam rock lobster. Grey shaded area indicates the 75% credible interval.



Annex 4

Annex 4: Equilibrium yield (t) and CPUE (kg/trap) for the reference case model for St. Paul rock lobster. Grey shaded area indicates the 75% credible interval.

