SERAWG-02-11

5th Meeting of the Southern Indian Ocean Fisheries Agreement (SIOFA) Scientific Committee

30 March – 03 April 2020, Saint Gilles, Réunion

Preliminary analysis of the Patagonian toothfish fishing data of the Del Cano Rise SIOFA

Relates to agenda item: SC5 item 7.4 & SERAWG2 item 4

Working paper ☒ Info paper ☐

Delegation of the European Union

Abstract

The part of the Del Cano rise (Del-Cano SIOFA) which is located in the southern part of the Southern Indian Ocean Fisheries Agreement (SIOFA) area has been subject to intermittent fishing effort targeting Patagonian toothfish (*Dissostichus eleginoides*) since 2003. While the fishing activity in this area was very limited in the first few years, the area has known two periods of higher effort between 2009-2013 and 2017-2019. Data from four countries which have previously participated in fishing for Patagonian toothfish were received and combined for this area. These data were used to fit Depletion models, CPUE standardization, and data-poor population models (CMSY, JABBA) to better understand the impact of these fisheries on Patagonian toothfish. The depletion approach demonstrated that at the scale of the area, CPUE has declined during the 8 months of continuous exploitation in 2017 and 2018 and that the CPUE did not appear to have recovered to pre-2017 levels by 2019. The abundance index estimated by CPUE standardization showed a trend of decrease concurrent with the highest catches of the time series in the years 2010-2013 and in 2017-2019, corresponding to the two periods of higher fishing effort. The abundance index also showed a strong increase of abundance between 2015 and 2017, possibly due to a simultaneous recovery of the stock and a change in the spatial distribution of the fishing effort. Data-poor population models have been adjusted with the catch data and the CPUE data. The preliminary results inferred that notable decreases in biomass corresponded to periods of higher fishing pressure. Those approaches are yet in early stage and would need more development and more data in order to estimate more robust catch limits. The document includes a set of recommendations addressed to the SC.

Recommendations

We recommend:

1. An evaluation of the efficiency of the data request process and data release detail for purposes of the work of the SC and its WGs,
2. The spread of fishing effort spatially and stratified across depth over as large a range as possible for the Del Cano region to obtain the information necessary to determine the potential for this fishery, avoid over-concentration of catch and effort, and attain representative toothfish biological data for biomass estimation and population characteristics
3. The update of the longline observer data template to include a record sheet for tag releases on toothfish
4. The development of a longer-term fishery-based research plan for the Del Cano region

Preliminary analysis of the Patagonian toothfish fishing data of the Del Cano Rise SIOFA

R., Sarralde[1], F., Massiot-Granier[2], J., Selles[2], M., Soeffker[3]

1 Instituto Español de Oceanografía, Centro Oceanográfico de Canarias, Vía Espaldón Dársena Pesquera PCL8, 38180 SC de Tenerife, Spain.

2 Laboratoire de Biologie des Organismes et des Ecosystèmes Aquatiques (BOREA), Museum national d'Histoire naturelle, 43 rue Cuvier 75005 Paris, France.

3 Centre for Environment, Fisheries & Aquaculture Science, Lowestoft NR33 0HT, United Kingdom

Abstract

The part of the Del Cano rise (Del-Cano SIOFA) which is located in the southern part of the Southern Indian Ocean Fisheries Agreement (SIOFA) area has been subject to intermittent fishing effort targeting Patagonian toothfish (*Dissostichus eleginoides*) since 2003. While the fishing activity in this area was very limited in the first few years, the area has known two periods of higher effort between 2009-2013 and 2017-2019. Data from four countries which have previously participated in fishing for Patagonian toothfish were received and combined for this area. These data were used to fit Depletion models, CPUE standardization, and data-poor population models (CMSY, JABBA) to better understand the impact of these fisheries on Patagonian toothfish. The depletion approach demonstrated that at the scale of the area, CPUE has declined during the 8 months of continuous exploitation in 2017 and 2018 and that the CPUE did not appear to have recovered to pre-2017 levels by 2019. The abundance index estimated by CPUE standardization showed a trend of decrease concurrent with the highest catches of the time series in the years 2010-2013 and in 2017-2019, corresponding to the two periods of higher fishing effort. The abundance index also showed a strong increase of abundance between 2015 and 2017, possibly due to a simultaneous recovery of the stock and a change in the spatial distribution of the fishing effort. Data-poor population models have been adjusted with the catch data and the CPUE data. The preliminary results inferred that notable decreases in biomass corresponded to periods of higher fishing pressure. Those approaches are yet in early stage and would need more development and more data in order to estimate more robust catch limits. The document includes a set of recommendations addressed to the SC.

Keywords – *Dissostichus eleginoides, Patagonian toothfish, Del Cano rise, Depletion model, CPUE standardization, Stock assessment, Population dynamic model.*

Introduction

The part of the Del Cano rise located in the southern part of the Southern Indian Ocean Fisheries Agreement (SIOFA) convention area (Del-Cano SIOFA) has been subject to intermittent fishing effort targeting Patagonian toothfish since 2003. While the fishing activity in the area was very limited in the first years, the area has known two episodes of more intense fishing between 2009-2013 and 2017-2019. The Del-Cano SIOFA area is of particular interest since it is adjacent to the South African Exclusive Economic Zone (EEZ) of Prince Edward and Marion Islands, the French EEZ of Crozet Islands and to the area of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) jurisdiction (Figure 1), each of which has management approaches to the local Patagonian toothfish stock.

The first evidence of Patagonian toothfish caught within the SIOFA convention area was in 2003 in the Del Cano Rise during an experimental fishing survey (López-Abellán, 2005). Since then, three other fishing nations have fished for Patagonian toothfish in the area (Figure 2), over the periods of 2004-2017, 2009-2013 and 2010-2017. The most recent operations in the area took place in the period 2017-2019.

Fishing data were collected by vessels flagged to four countries: Spain, France, Japan, and Korea. Data available are relatively heterogeneous in quantity and quality, especially data collected before 2010. Therefore, this region can be considered as data-poor due to the limited temporal and spatial coverage of fishing effort, and where fishing effort information is available, some divergence in data collection approaches. This context makes the understanding of the dynamic of the fleet and the stock more difficult.

In absence of a stock assessment model for the Del Cano-SIOFA region, a catch limit of 55 tonnes was established by the 2019 SIOFA Meeting of the Parties (MoP).

Several documents have been presented to scientific working groups in 2019:

- An analysis of the Patagonian toothfish stock from data collected from observers on board vessels that operated between 2017 and 2019 in SIOFA 51.7 and 57.4 areas has been presented both in SIOFA WG-SERA-19 (Sarralde and Barreiro, 2019) and CCAMLR WG-FSA-19 (Sarralde et al, 2019).
- An analysis of tag recaptures in the SIOFA convention area from Patagonian toothfish tagged in the CCAMLR convention area together with the data analysis was presented at CCAMLR WG-FSA-19 (SC-CAMLR-38/04). It provided support for the hypothesis of connectivity between the toothfish populations in the SIOFA area with those around Crozet, Kerguelen and Heard Islands.

As requested by SIOFA SC, this document aims at 1) exploring the available fishing data to assess the impact of the SIOFA fisheries on the stock of Patagonian toothfish in the Del-Cano rise area (Fig. 1), 2) develop preliminary proxies of fish biomass and 3) explore temporal trends in order to better understand the population dynamic of the stock.

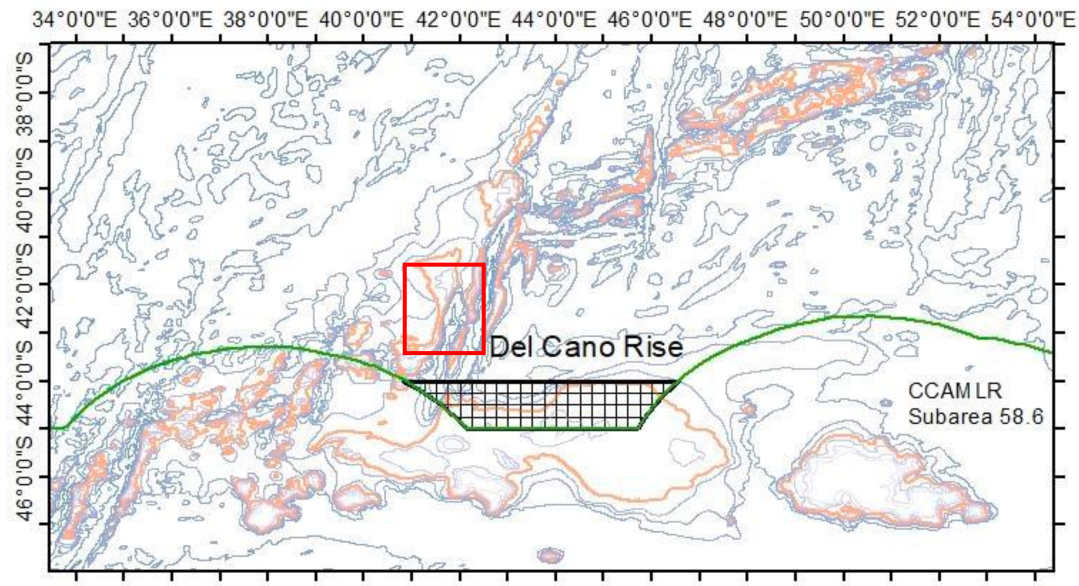


Figure 1. Patagonian toothfish fishing grounds in FAO area 51.7: The Del Cano SIOFA area (black grid, SIOFA-CMM 2019/15) and south of the West Indian Ridge (red block).

Material and Methods

Catch and data

A request for catch and effort data for the Del Cano region was made to the SIOFA Secretariat. Data from four Members which had historical catches in the Del-Cano SIOFA area were received with different levels of resolution and/or details. The key differences were as follows: datasets received from French (whole timeseries) and Spanish (since 2017) vessels included the catch in kg of Patagonian toothfish, number of hooks, soak time, date and location of setting and hauling, type of gear and fishing depth per line set in the water; these two datasets also include other variables collected during operations. Data received from Japanese vessels and some of the Spanish data before 2017 did not include the depth and details on hauling activities. All three datasets were available at the scale of per fishing line. Catch data received on Korean fishing activities were aggregated per year at the scale of the whole FAO area 51.

From the available data, 91% of the toothfish catches in the 51.7 area came from Del-Cano SIOFA (Korean data excluded, Figure 1, gridded in black) while the 9% of the remaining catch had been fished south of the West Indian Ridge to the north of Del-Cano rise (Figure 1, red block). These catches were not included in the analysis because of the geographical discontinuity between Del-Cano SIOFA and the West Indian Ridge.

Information about the Korean toothfish catch received was aggregated to the whole FAO 51 Area but since the only evidence of fishing for toothfish in this area is in the Del-Cano SIOFA and the Northern Ridge, we have included this catch in the total given Figure 2.

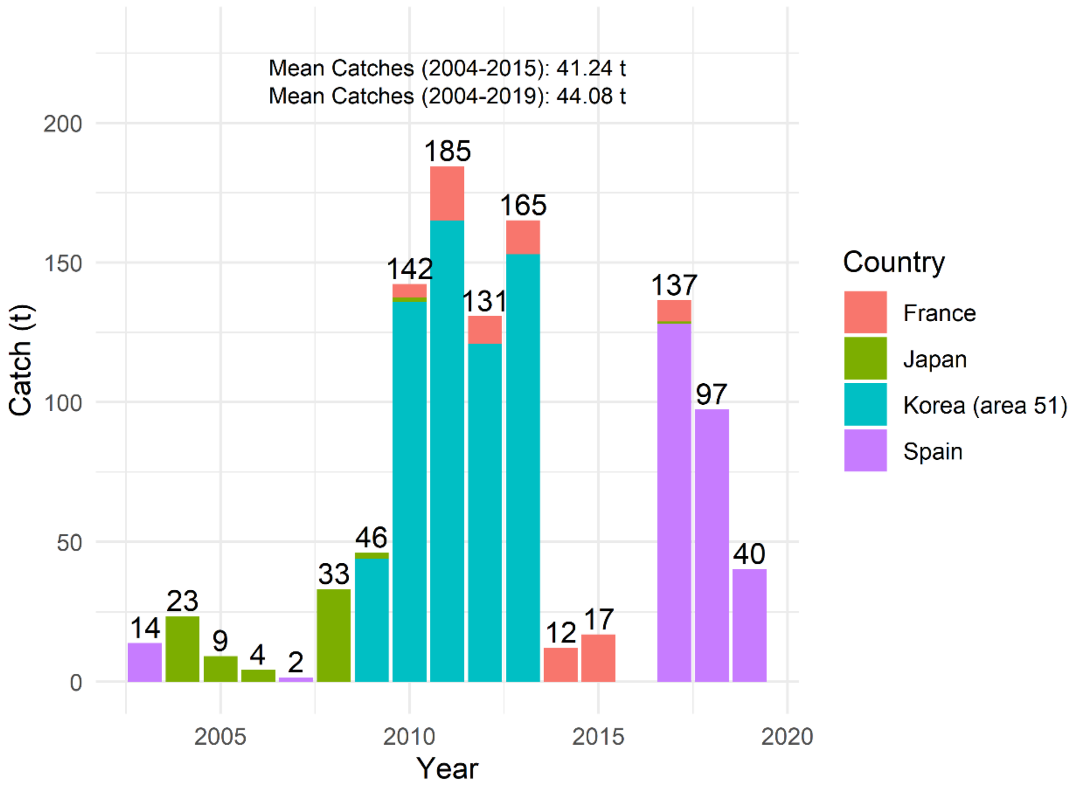


Figure 2. Catches of toothfish in the Del Cano SIOFA area from 2003 to 2019.

Depletion analysis

Depletion models have been widely used to estimate local abundance of fish stocks under the assumption that the relationship between CPUE and cumulative catch (Leslie and Davis, 1939) is linear. Local depletion analysis makes use of the fact that toothfish are territorial and usually move only a few kilometres each year (Agnew, 2004). This behaviour can lead to very localised depletion of toothfish in areas where a high-effort toothfish fishery operates. Therefore, the assumption is made that an adult toothfish does not move for periods of a few weeks up to a year, and fish are only replaced by immigration from adjacent areas over the scale of years (Agnew and Pearce, 2004, McKinlay et al., 2008). Within the Del Cano SIOFA region the bathymetry is deeper than 1 000 m and therefore it is unlikely that this region receives replacement through local recruitment, and thus this assumption was also made here. This process previously used to explore the use of depletion models at a local scale in the CCAMLR Convention Area, where a fisheries research plan was undertaken from 2012-2015 by means of a depletion experiment in Division 58.4.1 (Sarralde et al., 2014). The main difficulty at the time was to establish the relationship between the initial CPUE in the localised area where the depletion happened, and scaling the outcomes up to a resulting biomass for the entire Division. The large size of the fisheries research box within Division 58.4.1 made this aim difficult to achieve. Instead, in 2016, a new joint research plan between 5 CCAMLR members was put into place working jointly towards a regional stock assessment by collecting data following a common research plan and standardised data collection protocol.

The Del Cano SIOFA area is much smaller than CCAMLR Division 58.4.1 and fishing activities are more concentrated, and thus the depletion approach could be explored using data from Spanish vessels from 2017 to 2019. The presence of the French fleet almost every year from 2010 to 2017 could further be used as an additional depletion indicator in some small areas.

For the depletion approach to local biomass estimation, a series of clusters of sets where the fishing effort has been concentrated in time were identified as potential proxies for toothfish “hot spots” (higher abundances). Depletion series were defined so that (1) the time-lag between two consecutive sets does not exceed 30 days, (2) the maximum distance between all longline set[1] of a series and the centroid is 10 nm, and (3) includes at least 10 lines with toothfish catches. Once depletion series have been selected, significant[2] depletions were identified through regression analysis. A discrete time step of 30 days was chosen to identify each fishing campaign through the entire period (2003-2019). The size of the local areas was restricted to a circle of about 20 n miles diameter to get sufficient number of lines in the depletion series, which represents the double of the surface recommended in the 1993/94 CCAMLR experimental protocol presented in CCAMLR WG-FSA-94/22 (Jones and Parkes 1994).

The Leslie local biomass estimate B_0 was then estimated from the following linear equation for each depletion series:

$$CPUE_t = qB0 - qK_t \quad (1)$$

With q the catchability coefficient and K_t the cumulated catch taken prior to period t. Standard errors for the catchability and initial biomass size estimates are computed following Seber (2002). Confidence intervals were computed using standard large-sample normal distribution theory. Toothfish density was then estimated by dividing local biomass by the estimated size of the local area fished. Following Agnew (2004), the area fished is calculated this by considering the area under the outer positions of the longlines.

CPUE trend and standardization

Construction of annual indices of stock abundance based on catch and effort data is a major part in many fisheries’ assessments (Campbell, 2004). These can be used to calibrate age-based stock assessments, but

---

[1] Coordinates of a longline set is determined as the midpoint position from the start and the end of the hauling.

[2] Slope estimates p values<0.05.

frequently these indices are also the only source of information on the trend in abundances in data-poor cases, particularly in the absence of fishery-independent data.

The standardization of catch and effort data to develop an index of the relative abundance of a fish population assumes that the explanatory variables available are sufficient to explain most of the variation in the data that is not attributable to changes in abundance (Maunder, 2004). Helped by statistical methods (e.g. generalized linear model GLM), with adequate information and sampling effort and/or design, standardized catch rates against explanatory variables can provide a true trend of abundance.

The initial aim was to use all available data provided by the four Parties which have historically fished in this region for CPUE standardisation and timeseries reconstruction. However, as explanatory variables such as depth, fishing location, or soak time were available to varying degrees between datasets only the two datasets for which explanatory variables were available were used for the time being. The approach is therefore limited to the period 2010-2019.

Data poor stock assessment models

Finally, we also adapted two population dynamic models that could be used to assess data-poor areas. For both approaches, assumptions were made concerning the proportion of Korean catches potentially taken in the Del Cano SIOFA area. Based on available spatial distribution of catches from the remaining three fleets, we estimated and assumed that up to 91% of the Korean catch data could come from the Del Cano region in SIOFA. Two scenarios were then considered. The first scenario applies this rate to the Korean catch data provided at the scale of the whole 51 Area. A second scenario considered public information available[3], whereby for the period 2012-2013, Korean fishing vessels were seen widely distributed between the Del Cano SIOFA area, the West Indian Ridge, and adjacent waters, and thus in this scenario the assumption was made that a proportion of 50% of Korean catch data may have come from the Del Cano SIOFA area.

CMSY: Catch-MSY model

Catch-MSY methods (Froese et al., 2017; Martell and Froese, 2013) are widely used catch-only stock reduction analyses. Stock reduction analyses reconstruct historical abundance and exploitation rates by simulating biomass trajectories that could produce the observed catch time series given informative priors on initial and final year depletion and stock dynamics such as carrying capacity (*K)* or intrinsic growth rate (*r)* in the Schaefer model (Schaefer, 1954). The basic biomass dynamics are governed by:

$$B_{t+1} = B_t + \frac{r}{m-1}\left[1 - (\frac{B_t}{K})^{m-1}\right] \qquad (2)$$

[3] Global Fishing Watch, Washington, DC 20036, USA, https://globalfishingwatch.org/.

Where B_t is the annual biomass, K is the carrying capacity, r is the intrinsic growth rate and m is a shape parameter that determines at which B/K ratio the maximum surplus production is attained parameter.

In this study, we considered one set of priors for the intrinsic growth rate and the initial and final biomass depletion levels (Table 1). The CMSY method was implemented in R[4] with the 'datalimited2' library (Free et al., 2020) to estimate the biomass and exploitation rates.

Table 1. Summary of priors for the CMSY model Del Cano Rise toothfish.

Parameter	***Description***	***Prior***
R	Intrinsic growth rate	Uniform(0.1, 0.3)
$\varphi_{initial}$	Initial rate of biomass depletion	Uniform(0.8, 1)
$\varphi_{intermediate}$	Final rate of biomass depletion	Uniform(0.1, 0.6)
φ_{final}	Initial rate of biomass depletion	–

JABBA: State-Space Surplus Production Model

Surplus production models provide descriptions of harvested populations similar to the biomass dynamic introduced earlier with the CMSY model. The main difference lays in the observed equation linking the index abundance, the standardized CPUE, to the biomass level described by:

$$I_t = qB_t e^{\epsilon_t} \qquad (3)$$

Where q is the estimable catchability coefficient associated with the annual abundance index I_t and ε_t is the observation error.

The model was run for 30,000 iterations, sampled with a burn-in period of 5,000 for each chain, and thinning rate of five iterations. Basic diagnostics of model convergence included visualization of the MCMC chains throughout trace-plots as well as Heidelberger and Welch (Heidelberger and Welch, 1983), and Geweke (1992), and Gelman and Rubin (1992) diagnostics as implemented in the R '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).

---

[4] R Development Core Team, https://www.r-project.org/

We considered the same set of priors as in the previous approach for the intrinsic growth rate, the carrying capacity, and the initial biomass depletion levels (Table 2). The Bayesian State-space surplus production model JABBA was implemented in R with JAGS interface (Plummer, 2003) through the ‘’r2jags” library (Su and Yajima, 2012) to estimate the Bayesian posterior distributions of biomass and exploitation rates using Markov Chains Monte Carlo (MCMC) simulation.

Table 2. Summary of priors for the JABBA model Del Cano Rise toothfish.

Parameter	***Description***	***Priors***
K	Carrying capacity (t)	Lognormal-range(300, 3000)
r	Intrinsic growth rate	Lognormal-range(0.1, 0.3)
q	Catchability	Inverse-gamma (0.001, 0.001)
φ	Initial rate of biomass depletion	Lognormal(0.8,0.5)
σ_{η}^{2}	Process variance	Inverse-gamma (0.001, 0.001)
σ_{ε}^{2}	Observation variance	Inverse-gamma (0.001, 0.001)

Results

Data exploration

The average annual catch between 2003 and 2015 in Del-Cano SIOFA was 41.2 t, and from 2003 to 2019 the average annual catch was 48 t (Korean catches from 2009-2013 included).

Two different longline (LL) configurations were used in this region. Autoliners were used by France as well as one of the two Spanish vessels operating in the area. One Spanish vessel, as well as one Japanese vessel for one season, used the Spanish style LL, while the Japanese vessel used the trotline system LL for the remaining timeseries. There is no available information about the Korean fleet.

Catch per Unit of Effort (CPUE) data

Annual Catch per Unit Effort (CPUE) ranges from 23 to 267 kg per thousand hooks set, with the highest CPUE in 2006, 2008 and 2009 and the lowest in 2013, 2014 and 2015 (Figure 3).

France had the longest temporal series (2010-2017) and an overall low effort and CPUE per year. The French CPUE was significantly lower than CPUE reached on Spanish or Japanese vessels (Figure 3). Those differences suggest temporal changes in the availability of the resource but could also underline difference in fishing strategies between countries.

The aggregated data on Korean fishing activities showed operation from 2009 to 2013, starting prior to the French fishing operations and overlapping their activities between 2010 and 2013, a period where the French CPUE was continuously decreasing. The concurrence of these fisheries may have had an impact into the French CPUE but no information on the location of the Korean sets is currently available.

It is also noted that most lines set by Spanish vessels were hauled with a soak time of 107 hours on average. By way of comparison, the French lines were in the water for 33 hours on average (Annex 1). The potential importance of this difference in the analysis on the trend CPUE has been included in the CPUE standardization analysis.

Other data

At this stage, the biometry and biological data available from the Spanish and French fleet were not included in this paper but will be of future interest for the development of appropriate population dynamic models. Preliminary results are available in SERAWG-01-INFO-04 (Sarralde and Barreiro, 2019).

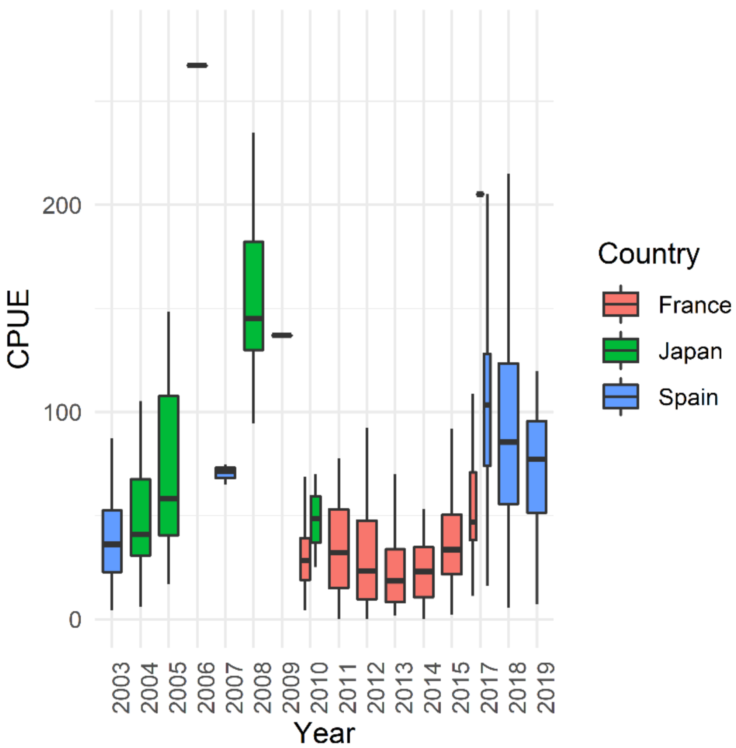


Figure 3. CPUE (kg/1000 hooks) of Patagonian toothfish in the Del Cano SIOFA area from 2003 to 2019 by country.

Depletion analysis

Del Cano SIOFA depletion analysis

Three consecutive periods of high fishing effort concentration have been considered in the depletion analysis to estimate biomass on the main fishing ground of the Del Cano SIOFA area. From October 2017 to February 2018, then from May to June 2018, two longliners have sequentially fished spread over the study region following a quasi-depletion experiment, giving the opportunity to estimate the initial biomass B_0 at 470 t (with a standard error of 104 t) by the end of 2017 (Figure 4). The fraction estimated to be captured by the these vessels is large over this period (274 t) representing more than 55% of the estimated initial biomass.

The vessels returned to this area from February to March 2019 and the resulting catch rates showed that CPUE did not recover to its 2017 level (less than 64 kg/1000 hooks on average), suggesting that with the given fishing effort, at this location the stock may need more than a year to return to pre-exploitation levels.

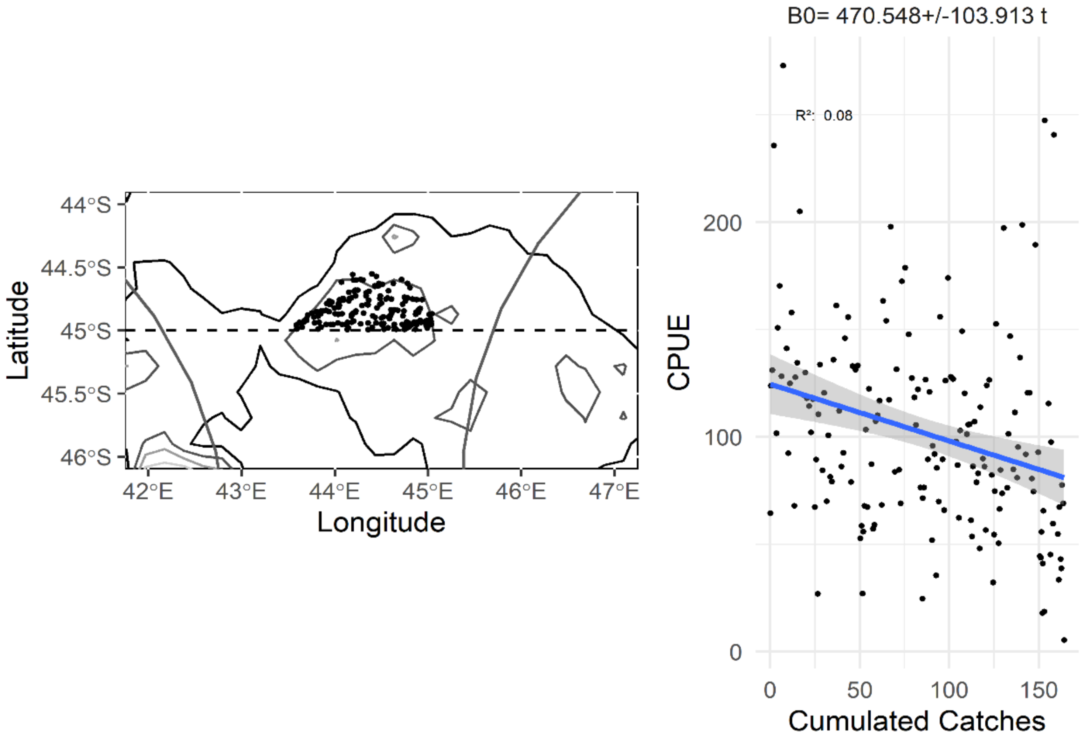


Figure 4. Depletion analysis of the Del Cano SIOFA for the period 2017-2018. Spatial distribution of longline sets (left, midpoint position from the start and the end of the hauling) and depletion estimation (right, CPUE in kg/1000 hooks against cumulative catches in tonnes).

Local depletion analysis

Over the evaluated time period, local depletions were only occasionally observed across the Del Cano Rise area. In total, 8 significant local depletions were detected in the Del Cano SIOFA area (see Annex 3 for details on subareas identified). Density estimates for each local depletion are given in Table 3, and are highly variable depending on the depletion series used.

In two subareas (A22 and A32) where multiple periods of depletion were identified, estimated densities showed high variations from low (<20 kg/km²) to high (>200 kg/km²) density between the period 2013-2015 and 2017/18. In subareas where local depletion series were only observed once, estimated densities were low in 2011 for subarea B and high for subarea A12 and C in 2017/18 and 2018 respectively.

The large differences observed between the low estimate of the initial densities in 2013, 2014 and 2015 and high estimated for densities in 2017-2018 might be due to concurrent fishing activities of the French and Korean vessels in the period 2009 - 2013 in the area (See Annex 2).

Table 3. Patagonian toothfish initial density (kg/km²) estimates per local depletion series of the Del Cano SIOFA for the period 2003-2019. Each depletion series identified is characterized by its subarea, year, number of vessels present in the depletion area, the number of vessels used in depletion area (i.e. Catch integrated in the cumulated catch fort the area), fishable area (km²), mean depth (m) and its initial CPUE (kg/1000 hooks).

Subarea	Year	Number of vessels in depletion area	Number of vessels used in depletion area	Fishable area (km²)	Mean depth (m)	Initial CPUE (kg/1000 hooks)	Patagonian toothfish initial density estimates (kg/km²)
A22	2013	1 French vessel Potential Korean vessels (unconfirmed)	1	371	1175	55.0	8.5
A22	2017-18	2 Spanish vessels	1	659	1240	64.5	223.0
A32	2014	1 French vessel	1	562	1364	34.8	6.1
A32	2015	2 French vessels	1	340	1318	29.1	19.0
A32	2017-18	1 French vessel 1 Spanish vessel	1	785	1373	123.8	225.0
B	2011	1 French vessel Potential Korean vessels (unconfirmed)	1	454	1621	215.3	10.9
A12	2017-18	1 Spanish vessel	1	377	1350	133.2	182.0
C	2018	1 Spanish vessel	1	292	1657	195.8	279.0

CPUE standardization

Model fitting and selection

The approach was limited to the French and Spanish datasets for the period 2010-2019 due to data limitations (see Methods).

Different models and combinations of variables were tested, and the chosen model as well as the step-wise model selection process are given in Equation (4) and Table 4. Second order effect of depth and the soak time were tested as their relationship was expected to be not linear with CPUE. Further included were interactions between the nationality of the vessels and the depth and soak time effects, which could reflect different fishing strategies by different vessels or fleets. Vessel effect on its own was not included since only few vessels fished more than once in the area making it impossible to dissociate the year effect from the vessel effect. Ultimately, the best fit model (Table 4, Equation 4, Annex 4) was selected based on its AIC (reverse 'StepAIC' procedure from R 'MASS' package).

$$\log(CPUE) \sim Depth + Depth^2 + Soaktime + Soaktime^2 + Country + Year$$
$$+Depth \times Country + Depth^2 \times Country + Soaktime \times Country + Soaktime^2 \times Country \quad (4)$$

Table 4. Model results for the saturated model and reverse stepwise model selections when on parameter was removed at a time using generalized linear models.

Model	**Residual Deviance**	**AIC**
Saturated	0.52	1249
- Country:Depth	0.53	1252.3
- Country:I(Depth^2)	0.52	1252.5
- Soaktime:Country	0.53	1255.1
- Country:I(Soaktime^2)	0.54	1257.5
- factor(Year)	0.59	1293.8

Standardized index of CPUE

The outcomes of the CPUE model and the standardized index of CPUE are given in Figure 5. The latter captures a first decrease between 2010 to 2014 and, while the index shows a fast increase after 2014 until 2017, there is a second decrease observed in the two most recent years. These two periods of decrease are concurrent with the largest catches in the area, those from 2009 to 2013 (Korean catch data in this period were not included in the CPUE standardisation) and those from 2017 to 2019 (Figure 2).

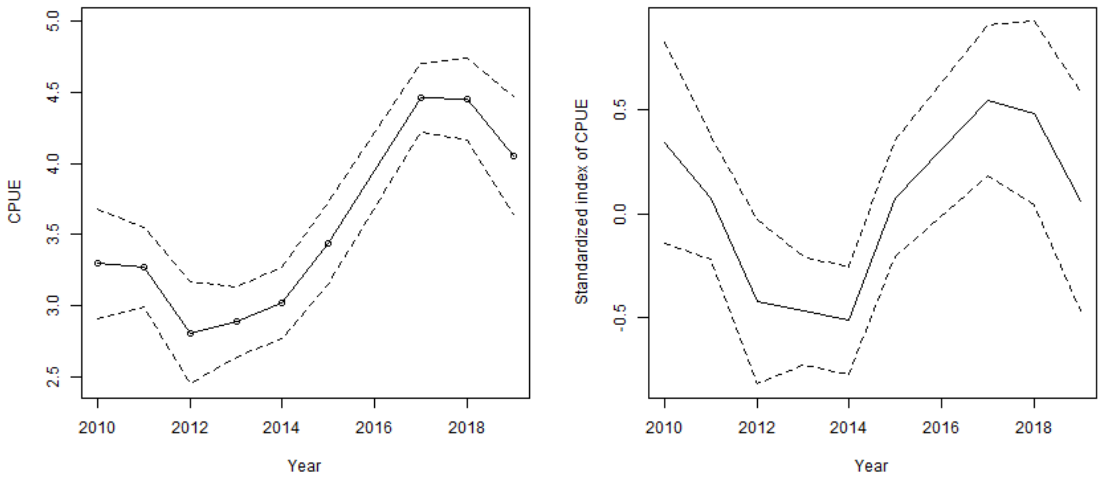


Figure 5. CPUE (left, kg/1000 hooks) and standardized index of CPUE scaled to a geometric mean of 1 (right).

Data poor assessment models

CMSY model

The relative biomass depletion (biomass over the carrying capacity or the pristine biomass, *B/K)* and the viable pairs of intrinsic growth (*r*) and carrying capacity (*K*) parameters are presented in Figure 6.

The model shows that after an initial period of low exploitation, a drastic decrease in the relative biomass was inferred to have occurred from 2010 to 2014 leading to a 49% loss of stock biomass. Despite the higher catches since 2017, the median relative biomass decreased slightly in the last period, but with large uncertainty. The initial relative biomass loss corresponds to the time period during and following the first set of higher catches in the timeseries in 2009 to 2013 (Figure 2).

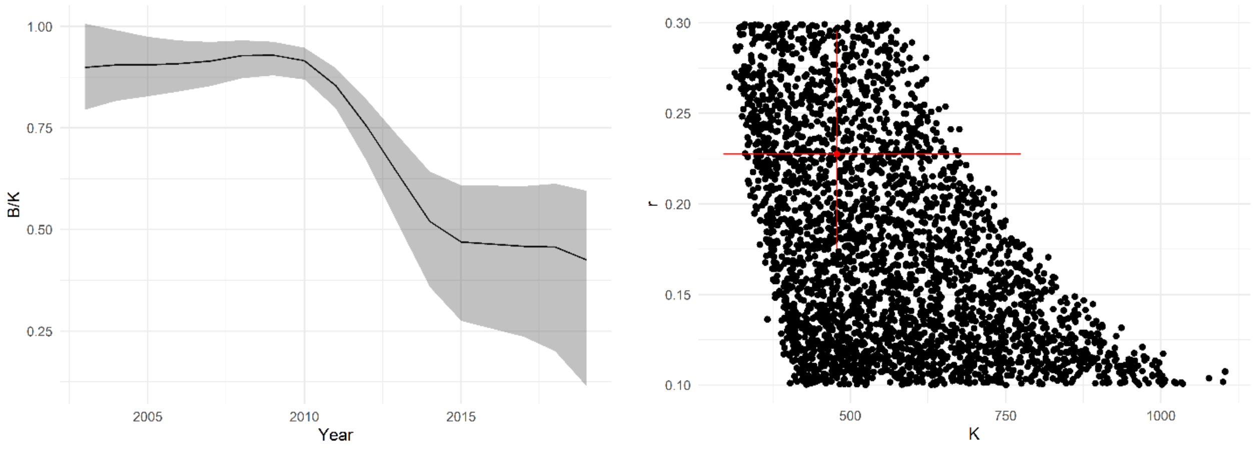


Figure 6. CMSY predictions of relative biomass B/K (bold curve) from 2003 to 2019 with 2.5th and 95th percentiles (left), and viable r-k pairs for Del Cano Rise toothfish (right) considering that 91.1% of the Korean catches occurred in the Del Cano SIOFA area.

A preliminary approach to assess the impact of two alternative historic catch distribution of FAO 51 aggregated data was explored and had a determining impact on the inference of viable *K*. The estimated median values for *K* change from less than 500 t to over 800 t depending on the assumptions made concerning the proportion of Korean catches during the 2009 to 2013 period occurring in the Del Cano SIOFA area.

JABBA model

All JABBA model runs showed robust convergence diagnostics, and the predicted CPUE index was compared to the observed CPUE to determine model fit (Annex 6). Plots of posterior densities together with prior densities were depicted in Annex 6.

The relative biomass depletion (biomass over the carrying capacity or the pristine biomass, *B/K)* and the posteriors pairs of intrinsic growth (*r*) and carrying capacity (*K*) parameters are presented in Figure 7.

The model inferred a drastic decrease in the relative biomass to have occurred from 2010 to 2013, similar to the CMSY model. Unlike the CMSY inferences, the CPUE-driven median relative biomass estimates a steep increase from 2014 to 2017, followed by decrease since 2017 which would correlate in time with the observed increased catches in 2017-2019.

The relative depletion estimate was not affected under the two alternative scenarios of distribution of FAO 51 aggregated data across the Del Cano SIOFA area, unlike inferences about the median size of the pristine biomass, which ranges from 300 to 700 t depending on the assumptions made concerning the proportion of catches during the 2009 to 2013 period occurring in the Del Cano SIOFA area.

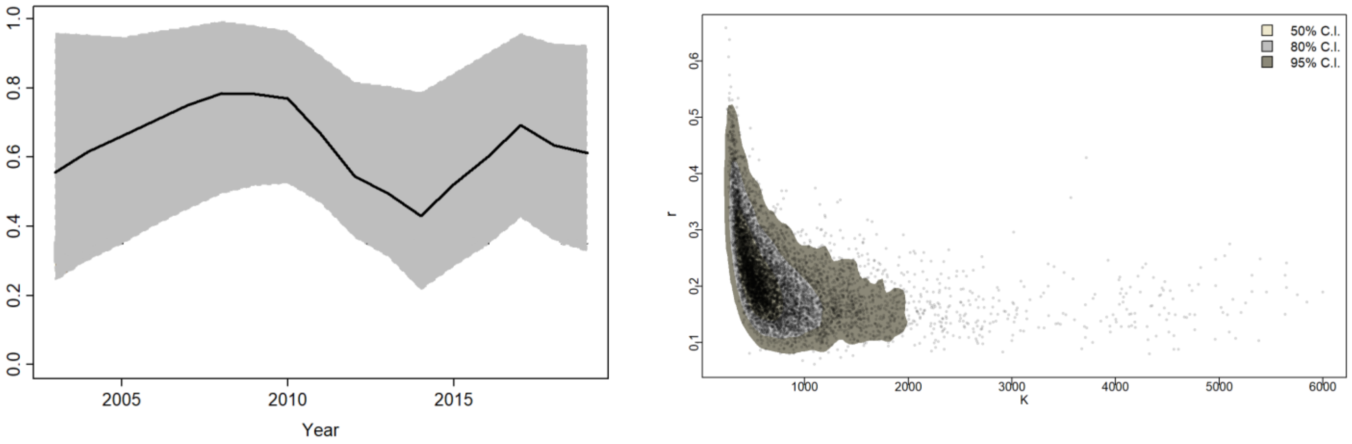


Figure 7. JABBA estimates of relative biomass *B/K* (bold curve) with 2.5th and 95th percentiles (left from 2003 to 2019), and posterior distributions of r-k pairs for Del Cano Rise toothfish (right) considering that 91.1% of the Korean catches occurred in the Del Cano SIOFA area.

Discussion

The depletion approaches showed that at the scale of the Del Cano SIOFA area, CPUE declined during the 8 months of continuous exploitation in 2017 and 2018 and did not recover to pre-2017 levels one year later in 2019. This suggests that the deployed exploitation rate did not allow for repletion of toothfish biomass in the local area within one year. It is not currently clear what the natural repletion rate of toothfish biomass in this region would be.

The exploration of local depletion in the data showed (1) that there is evidence of local depletion over the past 10 years, (2) local depletion observed with low catches might be due to concurrent catches for which CPUE were not available at this time and (3) as shown by the large variability of the densities estimated with depletion analyses, estimates of fish densities and pristine abundances are not likely to be accurate without specific sampling design.

The CPUE standardization provides insights on the trend of the abundance of the stock and reflected the periods of known increased fishing effort relatively well. The abundance index showed (1) a decreasing trend concurrent with the highest catches of the time series; between 2010 and 2013, and in the 2017-2019 period. The abundance index also (2) showed a strong increase between 2015 and 2017 after a period of low catches from 2013 to 2017. These fluctuations could reflect replenishment of local abundances from adjacent areas after periods of more intensive exploitation, or could be due to shifting fishing effort over time towards areas that had not previously been exploited, or may be a combination of both. Unfortunately, as the dataset was incomplete and fishing locations were not available for a subset of data at the time of writing, we could not explore this hypothesis.

The statistical modelling approach was limited from being utilised to its full potential as data had been collected sometimes systematically, sometimes opportunistically and without a coordinated data collection and sampling approach between fishing vessels. The lack of spatio-temporal overlap in fishing distribution meant that it was not possible to estimate a vessel effect, and only part of the catches taken in this region had associated effort data at the needed spatio-temporal scale. Combined effect of soak time and depth depending on the nationality of the fishing vessels shows important discrepancies in the CPUE relationship to those variables (Annex 5). It would be needed to include all catch and effort data from this region to improve the standardised CPUE timeseries reflecting the dynamics in this region. Going forward, inclusion of catch and effort variables to available data, recording of additional information such as number of fish caught but lost at the surface, the inclusion of tag release information, and spreading fishing effort and associated data collection over as large a geographical and bathymetric range as possible would improve information available for CPUE standardisation and biomass estimation in this region and likely improve the proportion of deviance explained by the models.

Finally, the data-poor population models were adjusted with the available catch and CPUE data and the preliminary results confirm a decrease of biomass following the initial period of higher exploitation (2009 – 2013) after which the stock did not return to levels prior to exploitation, with some models also inferring toothfish biomass decrease following the second phase of higher exploitation (2017-2019), suggesting that had this level of fishing pressure been maintained over a longer time period, the stock would likely have decreased beyond the point of replenishing itself. These approaches are yet in an early stage of development and would need more development and more data in order to estimate sustainable catch limits.

The preliminary standardised CPUE index as well as both data-poor modelling approaches show that the local biomass of toothfish responded to the exerted fishing effort, and the local depletion analyses provided further information on how the stock may fluctuate locally through fishery depletion and subsequent repletion. To prevent adverse and irreversible impacts of fishing pressure on the stock it would be necessary to develop and define meaningful reference points and biomass limits that allow for replenishment and recruitment, preventing a population decline to levels that could endanger stable recruitment of toothfish.

Conclusions and recommendations

The process of requesting catch and effort data across a region, and the resulting received data collected in the Patagonian toothfish fishery over the past 17 years highlighted the difficulties and challenges of working with data that was collected to different detail and aggregation level, making it difficult to reconcile. These difficulties with historic data showcased the substantial improvement made in recent years with the development of standardised data collection templates and development of regional measures, limits, and tag release programmes for toothfish. Our analyses of the available catch and effort data showed that over the past

17 years of Patagonian toothfish fishing in the Del Cano – SIOFA region there have been two events of higher fishing effort in the Del Cano SIOFA area that impacted the CPUE and the estimated stock status: a first between 2009 and 2013 by Korean fishing vessels which led to an initial reduction of biomass, and a second between 2017 and 2019 by Spanish vessels which shows, to date, a corresponding decline in CPUE, a sign of a decreasing local biomass. These patterns stress the need to consistently regulate fishing activities across the region to ensure a possible sustainable future of the Patagonian toothfish population in the area.

At the 2019 SIOFA Meeting of the Parties (MoP), a regional catch limit of 55 tonnes was adopted, with reference to the average catches from 2003 to 2015 in the Del Cano area. The information available since then and a recalculation with these data resulted in an average catch of 41.2 tonnes or lower per year, depending on the assumptions made on the distribution of Korean catches throughout Area 51. The currently applied 55 tonnes are higher than the historic average catch and higher than the annual catch in 9 out of 13 years. SIOFA does not, to date, have agreed biomass reference points or management targets for Patagonian toothfish.

The longline fishery for toothfish in adjacent CCAMLR has a much longer history, and there several levels of reference points, or Decision Rules, are used to ensure that the exploitation of toothfish remains sustainable in the long-term, resulting in highly precautionary catch limits consistent with the ecosystem objectives of CCAMLR. The Decision Rules for toothfish are set at two points. Firstly, the long-term spawning stock biomass of toothfish should remain at or above 50% of the initial unexploited biomass, so that the probability of the spawning biomass being too small to sustain itself is minimised. Secondly, the probability that the spawning biomass should decline below 20% of the initial biomass should be less than 10%. Together, these Rules guide the setting of sustainable and precautionary catch limits. CCAMLR has further developed approaches for setting preliminary catch limits where data are insufficient for integrated long-term stock assessments (SC-CAMLR-36/Annex 7, 2017, paragraph 4.33), a situation similar to Del Cano – SIOFA. Here, the trend of biomass estimation over available time, either estimated through tag-recaptures or through CPUE over a given seabed area, is evaluated to determine if the trend in the indices was increasing, stable, or decreasing. Following a set of rules, a maximum catch level is determined based on an exploitation rate that can increase catches where trends are increasing or stable, and decrease where trends are decreasing, based on the local biomass estimation. Annex 7 (as well as SC-CAMLR-36/Annex 7 paragraphs 4.28 to 4.37) provides the detail on this approach. This method allows for continued exploration and associated data collection towards longer-term assessment models, while at the same time annually adjusting the exploitation rate to local estimates.

The recommendation from the MoP in 2019 was that by its meeting in 2022 latest, the SC should be able to provide advice and recommendations on biologically appropriate catch limits for toothfish populations including at Del Cano (CMM 2019/15). Among the next steps, therefore, for the Del Cano region would be to work towards local and regional biomass estimations. To achieve this recommendation, and to improve our knowledge of the stock status for the Del Cano SIOFA area, it is necessary to establish a framework that would allow the development of a habitat model and a stock assessment model. This step would necessitate at minimum a tag-recapture programme consistent across all participants in the fishery as well as detailed and regionally consistent recording of fishing effort variables, in place as of 2020 for toothfish and highlighted through the difficulties encountered with historic data available at different detail and aggregation levels. It would also be necessary to receive data at an appropriate detail for the purposes of the work of the SC and its WGs. Additionally, to progress towards habitat models and spatially explicit models it would be necessary to implement a fishing strategy that includes spatial cover, depth stratification, and potentially spatial overlap over time. Such an approach should aim to improve the estimation of the CPUE-based abundance index and the resilience of the stock. A coherent and consistent strategy across the stock region, if set up as soon as possible, could be key to monitoring the response of the local stock to the recently observed higher fishing pressure. Additionally, the collection of consistent biometric data will be key to the model of the dynamic of the stock in order to assess the specific life traits in the area (e.g. growth curve).

While some fish tagged in the French and in the Australian EEZ have been recaptured in the Del Cano SIOFA area proving inward migration from these areas, to date not a single toothfish has been recovered from the South African EEZ. Indeed, the northward distribution of *D. eleginoides* is closely related to the extension of the Sub-Antarctic Front, and especially the intermediate layer of sub-Antarctic water masses, which defines the habitat of *D. eleginoides* toothfish. Del-Cano SIOFA could be at the northern edge of the global distribution area of *D. eleginoides* concentration, in which a residual recruitment effect persists (López-Abellán, 2005). The toothfish tagging protocol which is in force in the SIOFA convention area since 2020 (CMM 2019/15) will provide insights on the connectivity between this area and the close by fisheries of the South African EEZ and the French EEZ as potential future recapture of tagged fished in Del Cano SIOFA in EEZs would allow to assess the migration components.

To arrive at these points and be able to assess the local toothfish stock and its relation to adjacent areas, we therefore recommend:

1. An evaluation of the efficiency of the data request process and data release detail for purposes of the work of the SC and its WGs,
2. The spread of fishing effort spatially and stratified across depth over as large a range as possible for the Del Cano region to obtain the information necessary to determine the potential for this fishery, avoid over-concentration of catch and effort, and attain representative toothfish biological data for biomass estimation and population characteristics
3. The update of the longline observer data template to include a record sheet for tag releases on toothfish
4. The development of a longer-term fishery-based research plan for the Del Cano region

Bibliography

Agnew, D. J. 2004. Fishing South; the History and Management of South Georgia Fisheries. Penna, Press, UK, 128 pp.

Agnew, D.J. and J. Pearce. 2004. Estimating toothfish biomass in Subarea 48.3 using local depletions. Document WG-FSA-SAM-04/18. CCAMLR, Hobart, Australia.

Agnew, D. J., Edwards, C., Hillary, R., Mitchell, R. and Lopez-Abellán, L. J. 2009. Status of the coastal stocks of *Dissostichus* spp. in East Antarctica (Divisions 58.4.1 and 58.4.2). CCAMLR Science, 16,71-100.

Campbell, R. A. 2004. CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. *Fisheries Research*, *70* (2-3), 209-227.

CCAMLR, Fishery Report, 2018: *Dissostichus eleginoides.* Prince Edward Islands South African EEZ (Subarea 58.7 and part of Area 51)

CCAMLR Secretariat, 2018. Estimates of local biomass with uncertainty for Antarctic (*Dissostichus mawsoni*) and Patagonian (*D. eleginoides*) toothfish in research blocks in Subareas 48.6 and 58.4. WG-FSA-18/12. CCAMLR, Hobart, Australia.

Parker S.J. and D.C. Welsford, 2017. Procedures for proposals and reporting on research plans in data-poor fisheries. WG-FSA-17/13. CCAMLR, Hobart, Australia.

Free, C. M., Jensen, O. P., Anderson, S. C., Gutierrez, N. L., Kleisner, K. M, Longo, C., Minto, C. Osio, G. C.and Walsh, J. 2020. Blood from a Stone: Performance of Catch-Only Methods in Estimating Stock Biomass Status. *Fisheries Research* 223, 105452.

Froese, R., Nazli D., Gianpaolo C., Kristin M. K., and Winker, H. 2017. Estimating Fisheries Reference Points from Catch and Resilience. Fish and Fisheries 18 (3), 506-26.

Gelman, A. and Rubin, D. B. 1992. lnference from Iterative Simulation Using Multiple Sequences. *Statistical, Science*, 7, 457-472.

Geweke, J. 1992. Evaluating the accuracy of sampling-based approaches to the calculation of posterior moments., In: Berger, J. O., Bernardo, J. M., Dawid, A. P. and Smith, A.F.M. (Eds.), Bayesian Statistics 4: Proceedings of the Fourth Valencia International Meeting. Clarendon Press, Oxford, 169-193.

Heidelberger, P. and Welch, P. 1983. “Simulation run length control in the presence of an initial transient.” *Operations Research*, **31**, pp. 1109-44.

Jones, C. and Parkes, G. 1994. Determination of local density of *Dissostichus eleginoides* in Subarea 48.3 – CCAMLR protocol local depletion experiment Ihn Sung 66. CCAMLR, WG-FSA-94/22.

Leslie, P. H. and D. H.S. Davis. 1939. An attempt to determine the absolute number of rats on a given area. J. Anim. Ecol., 8: 94–113.

López-Abellán, 2005. Patagonian toothfish in international waters of the Southwest Indian ocean (statistical area 51). CCAMLR Science, Vol. 12 (2005): 207-214.

Martell, S. and Froese, R. 2013. A simple method for estimating MSY from catch and resilience. Fish and Fisheries 14, 504-514.

Maunder, M. N., and Punt, A. E. 2004. Standardizing catch and effort data : A review of recent approaches. *Fisheries Research 70* (2-3), 141-159.

McKinlay, J.P, D.C. Welsford, A.J. Constable and G.B. Nowara, 2008. An assessment of the exploratory fishery for *Dissostichus* spp. on BANZARE Bank (CCAMLR Division 58.4.3b) based on fine-scale catch and effort data. *CCAMLR Science*, Vol. 15 (2008): 55–78

Plummer, M. (2003). JAGS: A Program for Analysis of Bayesian Graphical Models using Gibbs Sampling, 3rd International Workshop on Distributed Statistical Computing (DSC 2003); Vienna, Austria.

Sarralde, R., López-Abellán, L. J. and Barreiro, S. 2014. Results of the Spanish exploratory longline fishery for *Dissostichus* spp. in Divisions 58.4.1 and 58.4.2 in the 2013/14 season. WG-SAM-14/12. CCAMLR, Hobart, Australia.

Sarralde R. and Barreiro, S. 2019. Patagonian toothfish population analysis with data from two Spanish vessels fishing in the South of the Indian Ocean (SIOFA CA) between 2017 and 2018. SERAWG-01-INFO-04. SIOFA-SERAWG. Yokohama (Japan).

Sarralde R., L.J. López-Abellán and S. Barreiro, 2019. Patagonian toothfish in the South Indian Ocean outside CCAMLR waters: a preliminary analysis of the SIOFA Patagonian toothfish population. CCAMLR, WG-FSA-2019/45

Schaefer, M. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bulletin of the Inter-American-Tropical Tuna Commission 1, 27-56.

SC-CCAMLR-XXXIII, 2014. Report of the thirty-second meeting of the Scientific Committee. (Hobart, Australia, 20 to 24 October 2014).

SC-CAMLR-36/Annex 7, 2017. Report of the Working Group on Fish Stock Assessment (Hobart, Australia, 2 to 13 October 2017).

SC-CAMLR-38/04. Report of the Working Group on Fish Stock Assessment (Hobart, Australia, 7 to 18 October 2019).

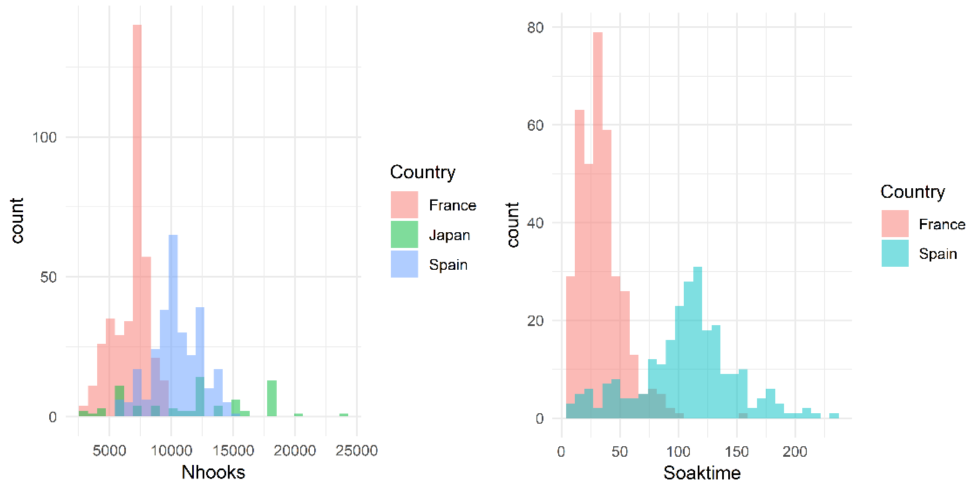
Seber, G. A. F. 2002. The Estimation of Animal Abundance and Related Parameters. Second Edition. Blackburn Press, New Jersey.

Su, Y.S. and Yajima, M. 2012. R2jags: A Package for Running jags from R.

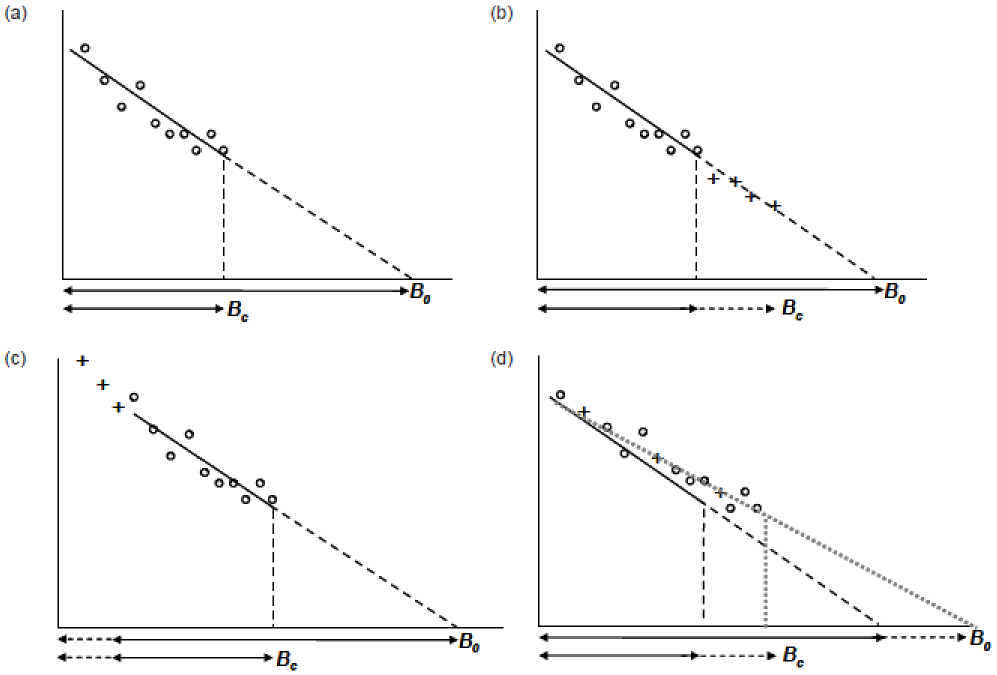
Winker, H., Carvalho, F. and Kapur, M. 2018. JABBA: Just Another Bayesian Biomass Assessment. Fisheries Research, 204, 275-288.

Annexes

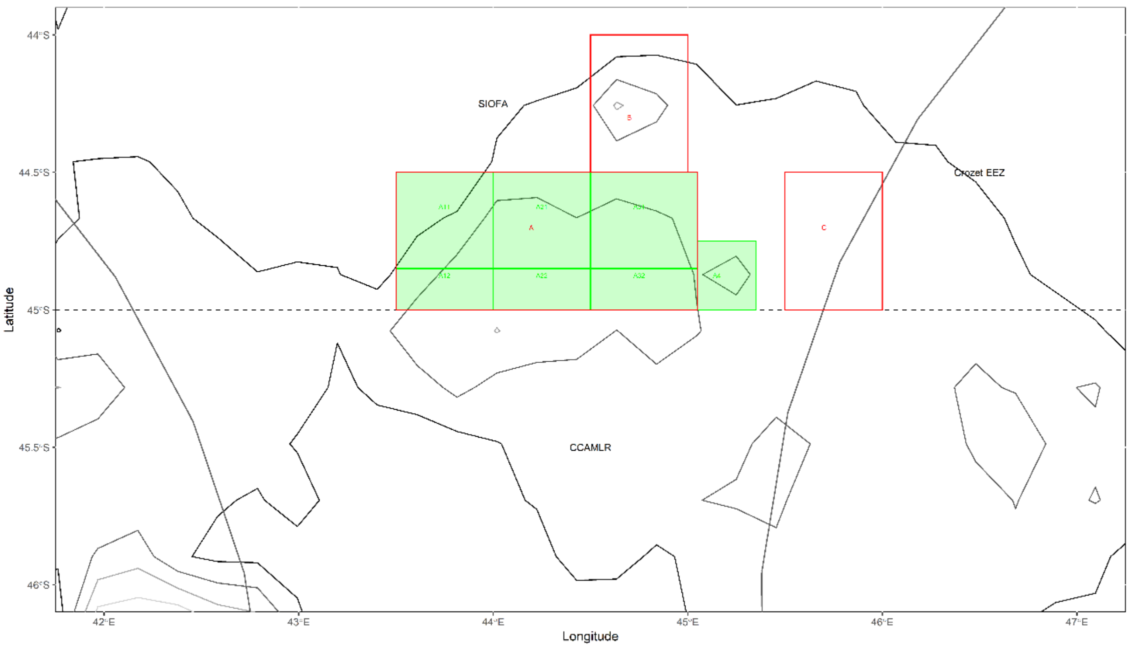
Annex 1: Histogram of soak time (right) and number of hooks (left) per line



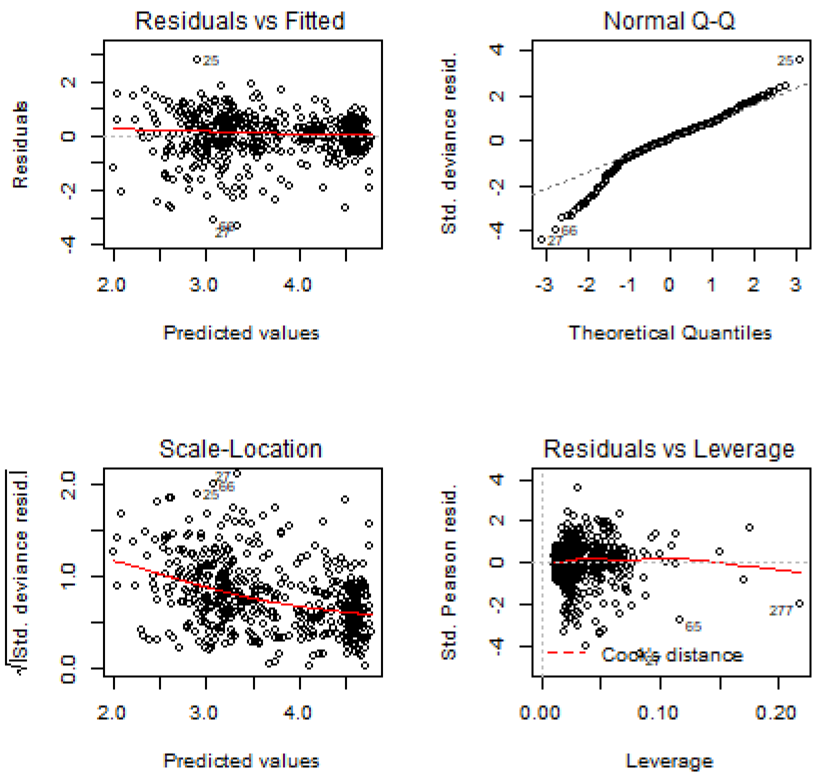
Annex 2. Hypothetical impact of the timing of non-observed fishing (crosses) on the local biomass (*N₀*), current biomass removals (*N_c*) and the rate of depletion (slope of the regression through the points) based on observed fishing (circles) from McKinlay et al. (2008). (a) Depletion due to observed fishing operations. (b, c) Represents situation where non-observed fishing occurs after, before the observed fishing operations. (d) When non-observed fishing occurs during the same period as observed fishing, No, Nc are underestimated and the rate of depletion is overestimated.



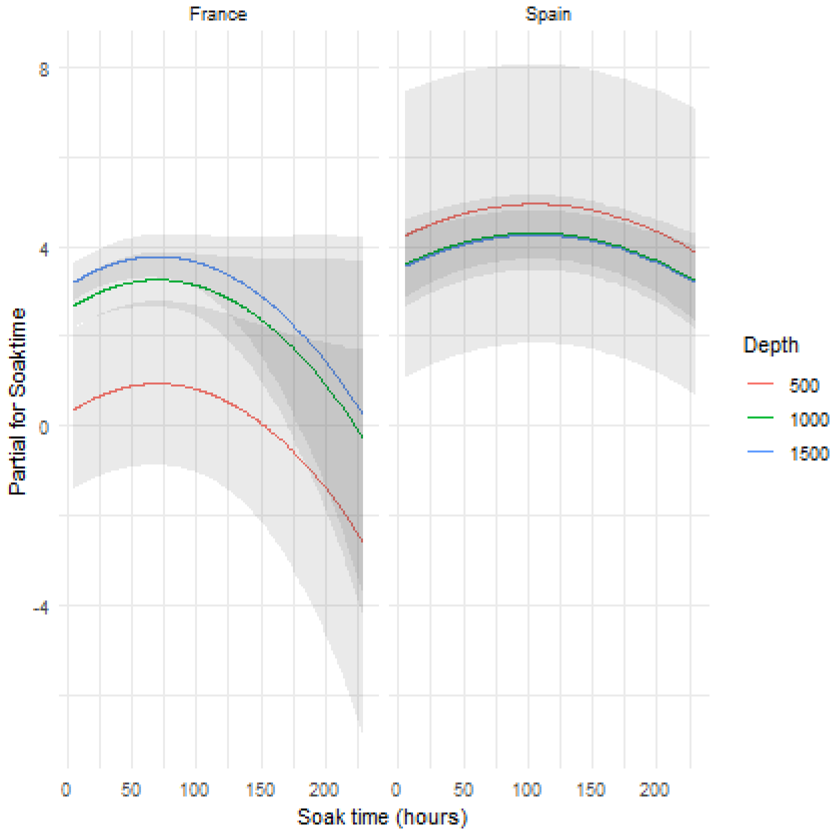
Annex 3. Map showing the location of all subareas of concentrated fishing that were investigated for local depletions



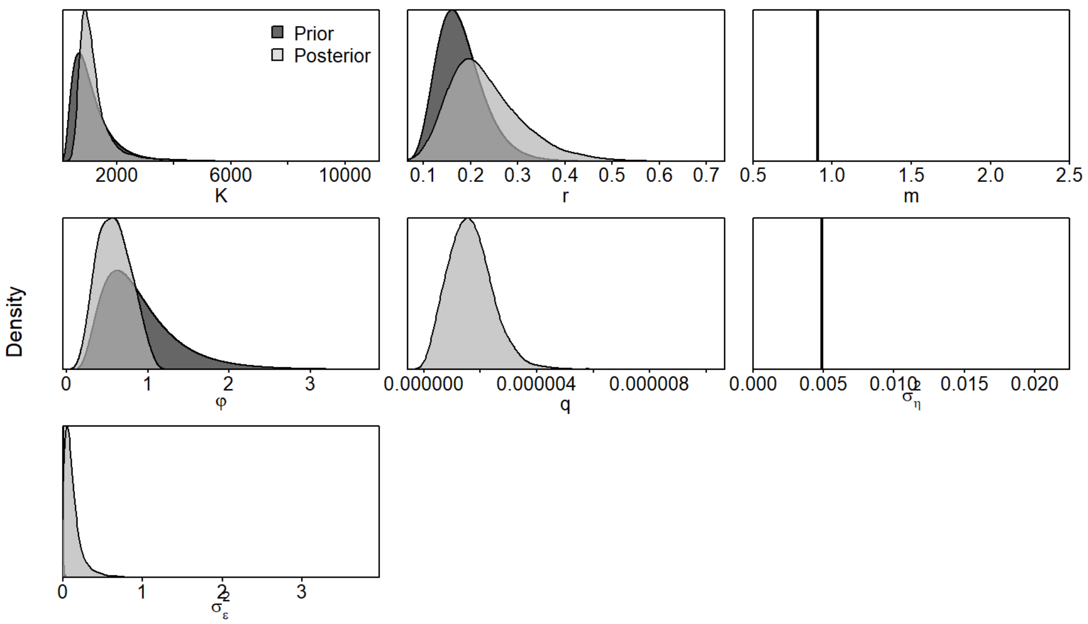
Annex 4. Diagnostic plots of Patagonian toothfish CPUE standardisation model

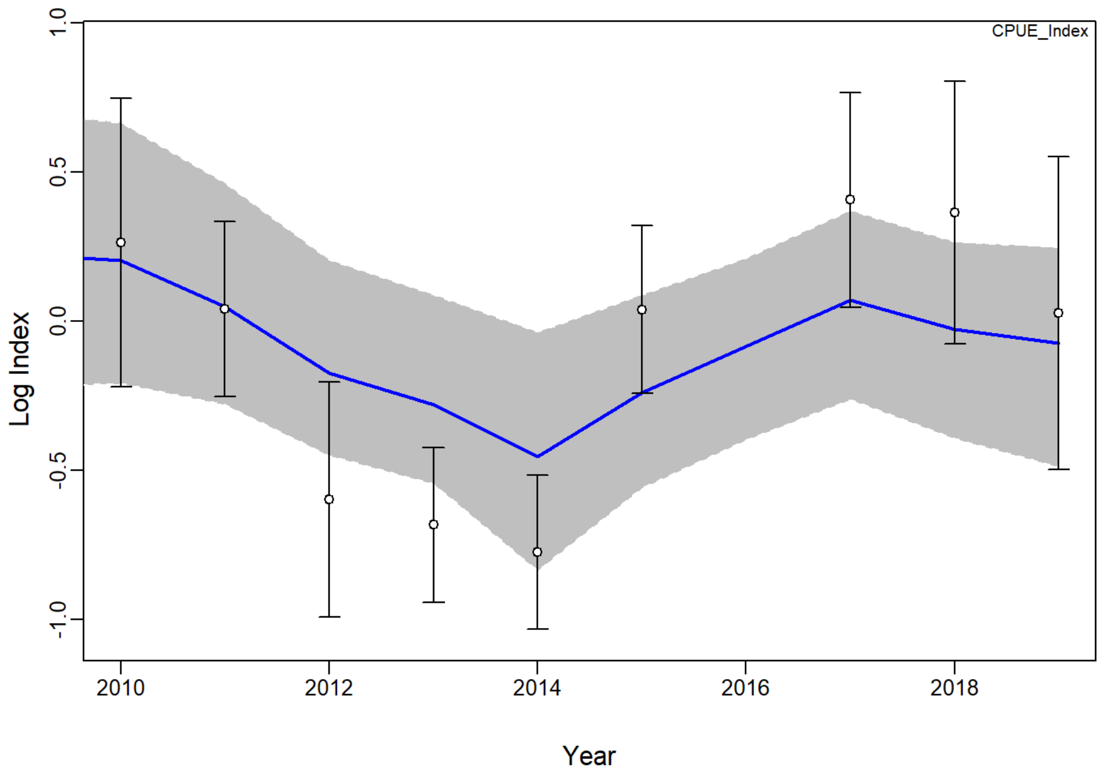


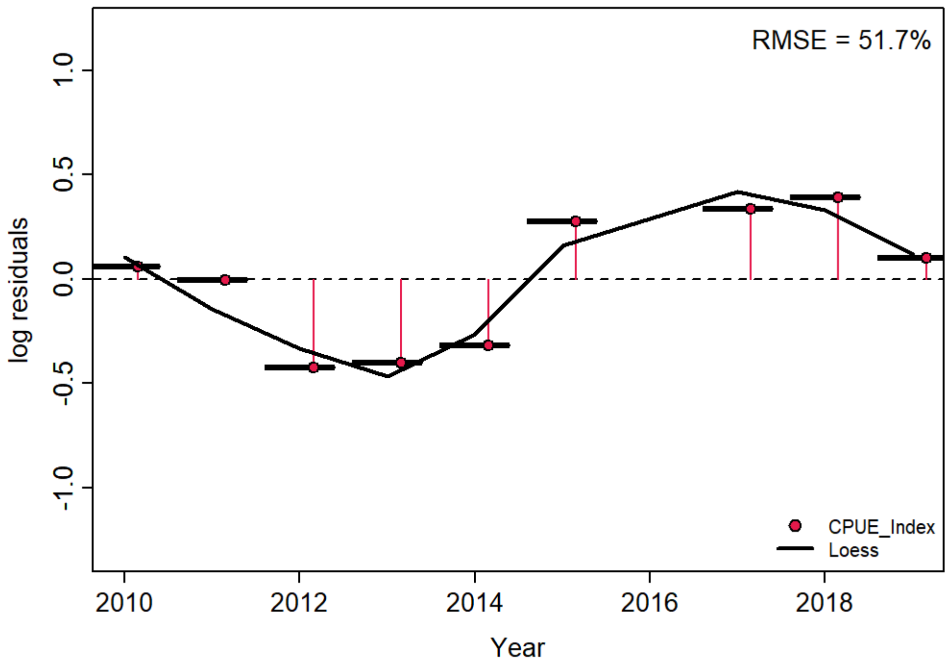
Annex 5. Partial fits of the saturated GLM to Patagonian toothfish CPUE for Soak time at different depth per country.



Annex 6. Priors and posteriors distributions for the JABBA model Del Cano Rise toothfish. Posteriors distributions are plotted using kernel densities estimates (top), fit of the catch per unit effort series (CPUE, center), and Residual diagnostic plots (bottom).







RMSE = 51.7%
log residuals
1.0
0.5
0.0
-0.5
-1.0
CPUE_Index
Loess
2010
2012
2014
2016
2018
Year

Annex 7. Trend analysis rules of CCAMLR for methodology and calculation of catch limits in data poor toothfish fisheries

In CCAMLR, a trend analysis following a set of rules was developed by WG-FSA-17 (SC-CAMLR-36/Annex 7, 2017, paragraph 4.33) for cases when it was not possible to estimate longer-term stock projection or in data-poor fisheries (CCAMLR Secretariat, 2018; Parker and Welsford, 2017). In these instances, there are local biomass estimates available derived from either tag-recapture based methods (Chapman, Petersen), or by scaling CPUE over a defined seabed area. Biomass estimates from the Chapman method are used if considered reliable, otherwise the CPUE method estimates are used. There is an additional constraint that resulting catch limits do not change by more than 20% per year.

The CCAMLR trend analysis rules for choosing a methodology for estimation and calculation of catch are (cited from SC-CAMLR-36/Annex 7, paragraph 4.33):

Apply a 4% exploitation rate to the Chapman and/or CPUE by seabed area biomass estimates, including up to the most recent season in which sampling has been completed for each research block (B4%):

- **IF** the trend was stable -
    - *if* adequate recaptures, use the B4% from the most recent Chapman estimate
    - *otherwise* use the B4% from the most recent CPUE by seabed area estimate
- **IF** the trend was declining -
    - use the current catch limit × 0.8 (regardless of adequate recaptures or not)
- **IF** the trend was increasing -
    - *if* adequate recaptures, use the B4% from the most recent Chapman estimate
    - *otherwise* use the B4% from the most recent CPUE by seabed area estimate.
- **IF** the trend was too short, too variable, or trends between abundance indices are in conflict –
    - *if* adequate recaptures, use the B4% from the most recent Chapman estimate
    - *otherwise* use the B4% from the most recent CPUE by seabed area estimate
- **AND** constraining any changes in the proposed catch limit to be not more than a 20% increase or decrease from the current catch limit.