Stock Annex 2021: *Dissostichus eleginoides* at Heard Island (Division 58.5.2)

CCAMLR Secretariat

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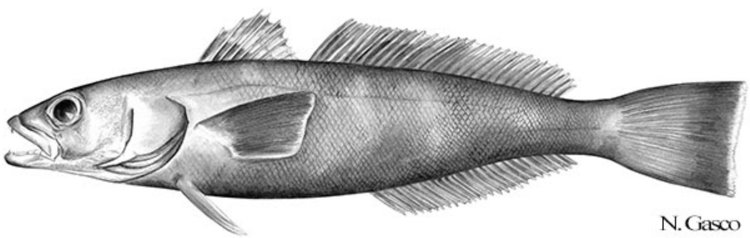
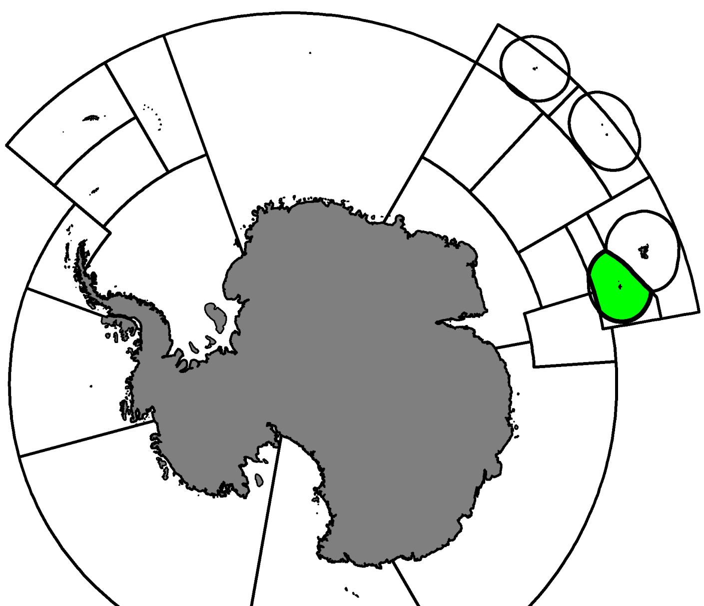


Patagonian toothfish *Dissostichus eleginoides* Smitt, 1898.



Map of the management areas within the CAMLR Convention Area. The region discussed in this report is shaded in green.

Stock Annex for the Patagonian toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.2

1. General

1.1 Stock structure and definition

The Kerguelen Plateau is located in the Southern Indian Ocean and stretches from around 45°S to over 60°S. Almost the entire Kerguelen Plateau is situated within the area managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), with only a small extension, the William's Ridge, on the eastern side of the northern part of the Plateau extending into the Southern Indian Ocean Fisheries Agreement (SIOFA) Statistical Area 7.

On the northern part of the plateau (north of Fawn Trough or roughly 57°S), two large fisheries for Patagonian toothfish are located in CCAMLR Division 58.5.1 which covers the French Exclusive Economic Zones (EEZ) around Kerguelen Islands, and Division 58.5.2 which covers the Australian EEZ around Heard Island and McDonald Islands (HIMI). On the southern part of the Kerguelen Plateau, Antarctic toothfish (*D. mawsoni*) which is better adapted to the colder waters around the Antarctic continent, is the dominant toothfish species.

Based on available genetic information (Toomey et al. 2016), catch composition (Péron et al. 2016) and tag-recapture data from survey and the commercial toothfish fishery (Burch et al. 2017, Ziegler et al. 2021), Patagonian toothfish are continuously distributed on the northern part of the Kerguelen Plateau and populations are linked. Within this area, the populations are likely structured with juveniles settling in shallow waters around the islands and potential exchange between Kerguelen Islands and HIMI (Figure 1). As fish grow larger and older, they move to deeper waters, and major spawning grounds are located on the western and southern side of the plateau.

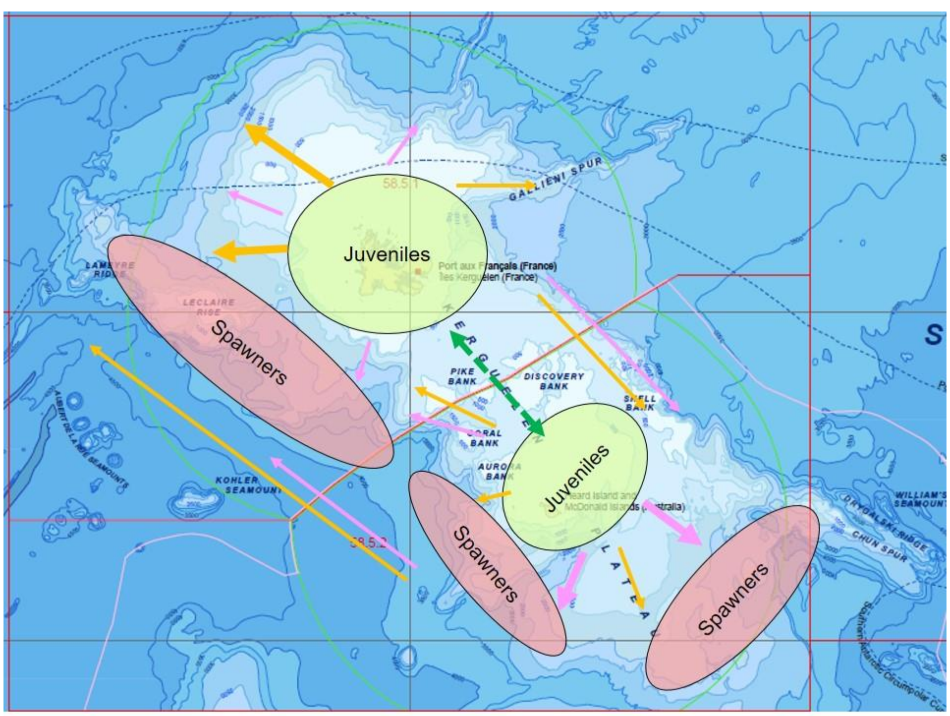


Figure 1: Schematic toothfish population structure on the northern part of the Kerguelen Plateau with Kerguelen Island to the north and Heard Island and McDonald Islands to the south. Juveniles settle in shallow waters on the plateau around the islands with potential exchange between areas (dark green arrows). Males (orange arrows) and females (pink arrows) then move into deeper waters as they grow larger and older, with major spawning grounds on the western and southern side of the plateau. Most adult fish move only short distances, but long-distance movement occur over the entire plateau, with some level of fish exchange between the Australian and French EEZ (green lines). CCAMLR Divisions are marked by red lines.

1.2 Fishery

Prior to the start of the Australian commercial fishery at HIMI, three random stratified trawl surveys (RSTS) were conducted in 1990, 1992, and 1993 to estimate the abundance and size structure of *D. eleginoides* and mackerel icefish (*Champsocephalus gunnari*) (Williams and de la Mare, 1995). Commercial fishing started in 1997, and trawl remained the dominant fishing gear for many years. Following the development of integrated weighted longline (IWL) to reduce the risk of seabird bycatch, longline gear was introduced in 2003. The catch taken by longline increased steadily over the years, and longline has become the dominant gear type since 2011. By 2017, almost the entire commercial catch was taken by longline. The use of traps were also trialled in 2006 and between 2009-2013 to prevent depredation by whales, but catches remained too small for traps to be commercial viable.

2. Catch data

The specifications for the catch data used in the 2021 stock assessment are provided in Table 1.

2.1 Commercial catch

Commercial catch data are reported by CCAMLR Members as both estimated catch on a haul by haul basis (C2 data) and landings by vessel and Division from the CCAMLR Dissostichus Catch Documentation (DCD) scheme (see Fishery Report). The haul-by-haul data from the RSTS, longline, trawl and trap included information on *inter alia* fishing date, haul latitude and longitude, fishing depth, gear type, effort, and total catch in weight and numbers.

Data from commercial hauls can be pooled into 'sub-fisheries' based on systematic trends in the catch-at-length distributions of fish in hauls following the method developed by Candy et al. (2013). The definition of sub-fisheries is typically based on gear-specific selectivity and fish availability in different locations, and sub-fisheries have individual selectivity functions to achieve a better model fit. The split between all gear types and depth split at 1500 m for longline hauls appear appropriate for the toothfish fishery in Division 58.5.2. For the stock assessment, the commercial sub-fishery structure for the assessment consisted of two trawl (Trawl1 and Trawl2), one trap (Trap), one shallow longline (LL1) and one deep longline sub-fishery (LL2).

2.2. Discards

Discarding of Patagonian toothfish is not permitted, and no discarding of dead toothfish has been reported by fishery observers.

2.3 Illegal, Unreported and Unregulated removals

Illegal, unreported and unregulated (IUU) catches in CCAMLR Division 58.5.2 were potentially large in the late 1990s and early 2000s (see Fishery Report). IUU catches were estimated based on sightings of IUU vessels, their known fishing capacities, and catch and effort data from the licensed fishery. No IUU vessel has been sighted after 2005 and it is likely that no IUU catches have been taken since then.

2.4 Other sources of mortality

Fishing-induced mortality from lost longline gear was estimated from the numbers of hooks that were lost. Gear loss was included when more than 100 hooks were lost at a time since incidental loss of small numbers of hooks and snoods may occur on longline operations without loss of any line, particularly at the transition between magazines. The numbers of lost hooks were then multiplied with the mean of catch per hook for that year as recommended by WG-SAM-19 (para. 3.5).

Between 2018 and 2020, there was also some fishing activity on the adjacent William's Ridge in SIOFA area 7.

Table 1: The specifications of the catch data used in the assessment for *D. eleginoides* in Division 58.5.2 in 2021.

Catch	**Years**
Survey	2001-2021
Trawl1	1997-2004
Trawl2	2005-2021
LL1	2003-2021
LL2	2004-2021
Trap	2006-2013
IUU	1996-2021
SIOFA	2018-2021
Gear loss	2003-2021

3. Biological parameters

The biological parameters used in the 2021 stock assessment are provided in Table 2.

3.1 Length-weight relationship

The parameters of the length-weight relationship:

Weight = $a(\text{Length})^b$

originally derived from Constable et al. (1999), were re-estimated for the 2019 assessment (Ziegler 2019). The estimated relationships varied slightly between 1997-2009 but has been highly consistent after 2009, and the length-weight relationship fitted to all data from 1997-2018 estimated a = 3.61E-12 and b = 3.1518.

3.2 Length-at-age

Length-at-age data was re-estimated in 2021 using all randomly sampled and aged fish from 1997-2020 (Ziegler 2021). Similarly to the 2019 assessment (Ziegler 2019) and as recommended by the CCAMLR Independent Stock Assessment Review (2018), a von Bertalanffy (vB) growth function was re-estimated that accounted for length-bin sampling and gear selectivity following the approach of Candy et al. (2007).

3.3 Stock recruitment relationship

Recruitment was assumed to follow a Beverton-Holt relationship, whereby stock-recruitment (SR) is assumed to be a function of the spawning stock biomass (SSB), the virgin spawning stock biomass (B_0), and the steepness parameter *h*, defined as *h* = SR(0.2 B_0), where:

$$SR(SSB) = \frac{SSB}{B_0} / \left(1 - \frac{5h-1}{4h}\left(1 - \frac{SSB}{B_0}\right)\right)$$

For Patagonian toothfish in Division 58.5.2, the stock recruitment relationship was assumed to have a steepness *h* = 0.75 following Dunn et al. (2006).

3.4 Natural mortality

Natural mortality for toothfish in Division 58.5.2 was estimated to be 0.155 (Candy 2011a, Candy et al. 2011) and assumed constant across all age classes.

3.5 Maturity

Yates et al. (2017) estimated the parameters of a logistic maturity function as a_{50} = 13.9 years and a_{to95} = 13.7 years (Figure 2). Yates et al. (2017) considered all stages ≥ 2 as mature since a large proportion of fish that were macroscopically determined to be stage 2 were found to contain cells of higher stages when gonads were examined histologically. This finding indicated that many fish that had spawned, as confirmed by the presence of post-ovulatory follicles, return to a resting stage which is macroscopically indistinguishable from maturing fish. Furthermore, the occurrence of females of all size classes with low gonadosomatic index (GSI) and low macroscopic gonad stage during the spawning season suggested that a proportion of mature fish did not spawn every year.

The assumption that all stages ≥ 2 are mature may bias the estimation of age-at-maturity in the population to some degree as some of stage-2 fish have not spawned in the past. Kock and Kellermann (1991) argued that the progression from cortical alveoli stage to hydration in notothenioid fishes can take up to 2 years. When adding an offset of 2 years to all stage-2 fish, the estimated age-at-maturity parameters were similar although contracted, with a_{50} = 13.7 years and a_{to95} = 10.6 years. The influence of the offset on the maturity parameter estimates was relatively small since maturity of young fish was strongly determined by a large number of stage-1 fish.

This maturity-at-age function predicted that some young fish in the age range of 1–7 would be mature which is inconsistent with the expectation of the life-history characteristics of a long-lived deep-water species. As for the 2019 assessment, the maturity function assumed that (Figure 2, Ziegler 2021):

(1) Fish aged ≤ 5 years: immature

(2) Fish aged > 5 years and < 10 years: Maturity increases linearly to the proportion as estimated under (3) for fish aged 10 years
(3) Fish aged ≥ 10 years: Maturity follows a function assuming fish of all maturity stages ≥ 2 are mature, with an age offset of 2 years added to all stage-2 fish.

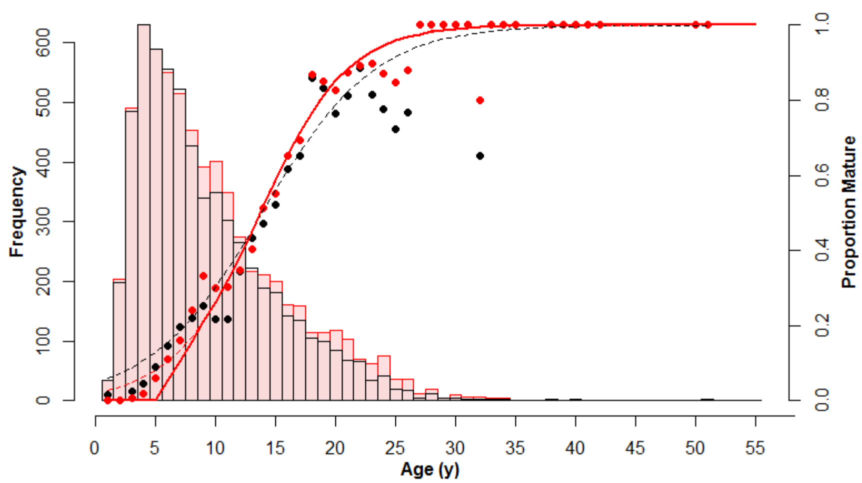


Figure 2: Maturity-at-age functions fitted to data assuming all fish of stage ≥ 2 are mature (black points and dashed black line, used in the 2017 assessment) and when an offset of 2 years to all fish of stage 2 was added (red points and dashed red line), and adjusted function assuming that all fish up to the age of 5 years are immature and maturity then increase linearly up to the estimated value at the age of 10 years (red solid line, used in this assessment). Shown are also age-frequency histograms and proportions of fish that were mature pooled in 1-year age bins (points).

Table 2: Biological parameters used in the assessment for *D. eleginoides* in Division 58.5.2 in 2021.

Parameters	**Specifications**
Length-at-age:	von Bertalanffy
L_∞	1504
K	0.058
t_0	-3.30
CV	0.135
Weight at length L (mm to t)	c = 3.61E-12, d = 3.1518
Maturity	Logistic: a_{50} = 13.7 a_{to95} = 10.6 Adjusted for ages < 10 y
Natural mortality M	0.155
Stock–recruitment relationship	Beverton-Holt Steepness h = 0.75

4. Abundance and other observations

The specifications for the abundance and other observations used in 2021 the stock assessment are provided in Table 3.

4.1. Random stratified trawl survey

The RSTS have been conducted in Division 58.5.2 to estimate the abundance and size structure of *D. eleginoides* and *Champsocephalus gunnari* (mackerel icefish) in 1990, 1992, 1993, and annually since 1997. However, the structure and intensity of the surveys has varied over these years as the objective for the surveys has changed, and information for survey design and power has improved (Welsford et al. 2006). Major surveys incorporating a wider range of toothfish habitats started in 1999, although for the first four years different stratum plans based on specific research questions for toothfish and icefish resulted in varying effort to survey toothfish. The large shallow strata sampled in the 1999 survey were subdivided in 2001 and the deeper strata in 2002, after which the strata boundaries have been stable. In 2000, only a relatively small area was surveyed, and the northern plateaus were not sampled in 2003. After reviewing the statistical power of the surveys in 2003, trawl allocation to strata with greater fish abundance was increased (Candy et al. 2004).

Since 2003, an annual survey has consisted of between 120-160 trawl hauls, each taking approximately 30 mins tow time on the seabed to complete. The entire fishable area in Division 58.5.2 down to 1000 m is divided into ten strata (of which one is excluded from sampling since it is closed to fishing), each covering areas of similar depth and/or fish abundance (Miller et al. 2021).

Survey observations were separated into a survey biomass index and survey proportions-at-age. The annual survey biomass and *CVs* for 2001-2002 and 2004-2020 were estimated as the sum of biomass estimates in each surveyed stratum which were derived from a stratified bootstrap of the estimated fish density in survey hauls. A uniform-log prior for survey catchability q was used in the assessment to account for the multiplicative space within which catchability is applied (Punt and Hilborn 2001).

4.2 Tag-release and recapture data

Tagging of *D. eleginoides* in Division 58.5.2 commenced in 1998 soon after the fishery had started. Initially, all tag-releases and recaptures were from trawl. However, trawl effort has been highly concentrated on a small fishing ground, and Candy and Constable (2008) investigated the inclusion of trawl tag-release and recapture data in the stock assessment. They concluded that these tag-recapture data were likely to only estimate the local biomass in the relatively small fishing area where trawl had been concentrated, rather than that of the population biomass in the entire Division 58.5.2.

Longlining started in 2003 on shallower fishing grounds in the eastern part of the Division and has expanded substantially to deeper fishing grounds and up to the northwest corner over the years. Within this trend, the spatial effort distribution has varied substantially between years. While tagged toothfish are unlikely to mix completely within the fished part of the population (Williams et al. 2003, Welsford et al. 2007, Welsford et al. 2014, Ziegler et al. 2021), only longline-caught fish that have been tagged and released from 2012 onwards have been used in the assessment since longline effort had been spatially more spread out from that year onwards.

Annual tag-release and recapture numbers from longline have increased since 2008, and particularly since 2015 due to a higher catch limit and an increase in tagging rates from 2 fish per 3 tonnes to 2 fish per tonne. In total, over 41 000 fish have been tagged and released and over 5200 have been recaptured since 2012.

In the assessment model, the numbers of longline tag-releases and tag-recaptures used were capped at 6 years at liberty to account for tag-shedding rates in CASAL being specified for fish tagged with a single tag, while all released fish are double tagged (Candy 2011b; Dunn et al. 2011), and within-season recaptures were excluded. Tag-release mortality was assumed to be 0.1 (Agnew et al. 2006), and a no-growth period after tagging of 0.5 years was assumed (Agnew et al. 2005).

The tag-detection rate during longline fishing was assumed to be to 100%, and tag-shedding rates were estimated following the method proposed by Adam & Kirkwood (2001) as estimated by Ziegler (2017). The parameter of annual tag loss rate in CASAL's single-tag model was then approximated for a maximum time at liberty of 6 years as l = 0.021 for 2007-2011 and l = 0.006 for 2012-2015. The same tag-shedding rate of l = 0.006 was also assumed for all tagged fish released since 2015.

4.3 Catch-at-age

A large number of toothfish have been measured annually for length in the RSTS and the commercial fishery, and over 22 000 fish ages have been estimated by technicians following the recommendation of the 2012 toothfish ageing workshop (SC-CAMLR 2012) and the protocols for thin sectioning developed at the Australian Antarctic Division (AAD; Welsford et al. 2012, Farmer et al. 2014, Ziegler et al. 2021). Year-specific ALKs, grouped by 50 mm length bins from 150 to 2000 mm were calculated separately for the survey and the commercial catch from all respective age-length samples.

For all surveys where ALKs were available (2006-2020), catch-at-length data were used to estimate proportions-at-length, weighted by stratum area. These were then converted to proportions-at-age, using survey ALKs. The initial effective sample size (ESS) for these survey proportions-at-age were derived by assuming a relationship between the observed proportions-at-age O_j and their CVs c_j as estimated from bootstrap sampling that accounted for haul-specific proportions-at-length, the ALK and random ageing error. The estimated effective sample size was then derived using a robust non-linear least squares fit of $\log(c_j) \sim \log(O_j)$ assuming a multinomial distribution.

For the commercial fishery, representative ALKs were available for all years from 1998 - 2020. Catch-at-length data grouped by 50 mm length bins from 150 to 2000 mm were used to estimate catch proportions-at-length and converted to proportions-at-age using commercial ALKs. Similarly to the survey data, initial ESS for all years and sub-fisheries except Trap were estimated by fitting a robust non-linear least squares model to the observed proportions-at-age against their CVs assuming a multinomial distribution. For Trap, ESS was set to 1 to allow for the estimation of trap selectivity while the information content of the data was considered to be poor due to high inter-annual variability in areas and depths fished.

In 2014, the method of Candy et al. (2012) to estimate the ageing error matrix (AEM) was revised by Burch et al. (2014) to address some issues regarding true ages not being the mode at the extremes of the matrix and a lack of smoothness in the probabilities for ages above 25 years.

Table 3: Abundance and other observations used in the assessment for *D. eleginoides* in Division 58.5.2 in 2021.

Observations	Specifications
RTSS:	Survey
Biomass index	2001–2020
Survey numbers at age	2006–2020
Estimated sample size (ESS)	Estimated (Francis 2011a, 2011b)
Commercial sub-fisheries:	Trawl1, Trawl2, LL1, LL2, Pot
Proportions at age	1997–2020
Estimated sample size (ESS)	Estimated (Francis 2011a, 2011b), except set to 1 for Pot
Ageing error matrix	Estimated (Burch et al. 2014)
Tagging data	
Release sub-fisheries	LL1, LL2
Years	2012–2019
Recapture sub-fisheries	LL1, LL2
Years	2013–2020
Tag detection	1.00
Tag shedding	0.06
Tag-release mortality	0.1
Emigration correction	0.01 (included in tag shedding parameter)
No-growth period	0.5 y

5. Assessment

5.1 Methods

The single-sex CASAL assessment model (Bull et al. 2012) was age-structured with age classes from 1-35 years. CASAL 2.30-2012-03-21 rev. 4648 was used in all instances, following the recommendation of WG-SAM-14 (WG-SAM-14, para. 2.29).

The specifications for the 2021 assessment model and estimated parameters are provided in Table 4.

The assessment models were run for the period from 1982-2021. The annual cycle was divided into three time steps or seasons during which (1) fish recruitment, the first half of natural mortality, and fishing, (2) the second part of natural mortality and spawning, and (3) ageing occurred.

Either double-normal (DN) or double-normal-plateau (DNP) fishing selectivity functions were fitted for the survey and each sub-fishery. The DNP function was calculated as *f(x)* for age *x* (Bull et al. 2012):

$$f(x) = \begin{cases} a_{\max} 2^{-\left[(x-a_1)/\sigma_L\right]^2} & x \le a_1 \\ a_{\max} & a_1 < x \le a_1 + a_2 \\ a_{\max} 2^{-\left[\{x-(a_1+a_2)\}/\sigma_U\right]^2} & x > a_1 + a_2 \end{cases} \quad (1)$$

where a_1 and a_1+ a_2 define the age range at which the ogive takes the value a_{max}, and σ_L and σ_R define the shape of the left-hand and right-hand side of the DNP function such that the ogive takes the value 0.5a_{max} at $a = a_1 - \sigma_L$ and $a = a_1 + a_2 + \sigma_R$. In all cases, a_{max} was not estimated but set to 1, i.e. only four parameters were estimated for all DNPs. When the parameter a_2 is estimated to be very small (~ 0.1 year), the DNP collapses to a DN and was replaced with a DN function in the assessment model. This was the case for the survey, the trawl and longline sub-fisheries (see below), while the trap sub-fishery was fitted with DNP functions.

The assessment models estimated the unfished spawning biomass B_0, survey catchability *q*, annual year class strength (*YCS*), and the parameters of the selectivity functions for the survey and all sub-fisheries.

All models included penalties for *YCS* and catch. A penalty for *YCS* was intended to force the average of estimated *YCS* towards 1. Strong catch penalties prohibited the model from returning an estimated fishable biomass for which the catch in any given year would exceed the maximum exploitation rate set at U = 0.995 for each sub-fishery.

Process error was estimated and added in a number of iterations following the method TA1.8 described by Francis (2011a and 2011b) to allow for correlations within the observed composition data. The reweighting was applied first to the commercial catch composition data of all sub-fisheries, then to the survey composition data, and lastly to the tag-recapture data.

For catch-at-age composition data, the weight w_j for each age *j* observed by a sub-fishery or the survey was estimated as:

$$w_j = \frac{1}{\mathrm{var}_i\left[(O_{iy} - E_{iy}) / \sqrt{(v_{iy} / N_{iy})}\right]} \tag{2}$$

where O_{iy} is the observed and E_{iy} is the expected proportions for age or length class *i* in year *y*, v_{iy} is the variance of the expected age or length distribution, and N_{iy} was the number of multinomial cells. The weight was then multiplied with the sample size from the previous step before re-running the model. For the re-weighting of the tagging data, Equation (2) was used again.

Initially, a point estimate (maximum posterior density MPD) and its approximate covariance matrix for all free the parameters as the inverse Hessian matrix were estimated. For the final model, these estimates were used as starting point for Monte Carlo Markov Chains (MCMCs) sampling. For the MCMCs, the first 500 000 iterations were dismissed (burn-in), and every 1000th sample taken from the next 1 million iterations. MCMC trace plots were used to determine evidence of non-convergence.

5.2 Yield calculations

Catch projection trials accounted for uncertainty surrounding parameter estimates of the model as well as future recruitment variability. In order to integrate across uncertainty in the model parameters, MCMC samples were used for CASAL's projection procedure to obtain 1000 random time series samples of estimated numbers of age-1 recruits for the period from 1982-2015, corresponding to *YCS* estimates from 1981-2014. The median of the square root of the variance of the yearly numbers of these age-1 recruits from 1986-2015 provided a robust estimate of the σ_R for recruitment required for the lognormal random recruitment generation.

The estimated *CVs* were used to generate the random recruitment from 2016 until the end of the 35-year projection period. Based on this sample of projections for spawning stock biomass, long-term catch limits were calculated following the CCAMLR decision rules:

- Choose a yield γ_1, so that the probability of the spawning biomass dropping below 20% of its median pre-exploitation level over a 35-year harvesting period is 10% (depletion probability).
- Choose a yield γ_2, so that the median escapement of the spawning biomass at the end of a 35-year period is 50% of the median pre-exploitation level.
- Select the lower of γ_1 and γ_2 as the yield.

The depletion probability was calculated as the proportion of samples from the Bayesian posterior where the predicted future spawning biomass was below 20% of B_0 in the respective sample at any time over the 35-year projected period. The level of escapement was calculated as the proportion of samples from the Bayesian posterior where the projected future status of the spawning biomass was below 50% of B_0 in the respective sample at the end of the 35-year projection period.

Catch limit estimates were based on the assumption of constant annual catches. Future surveys were assumed to be conducted every year with a catch of 20 tonnes. The entire remaining future catch was assumed to be taken by longline, with a catch split based on the overall catch distribution of longline sub-fisheries in the last three years, i.e. 60% of the total catch was attributed to LL1 and 40% to LL2 selectivities.

Table 4: Model specifications for estimated parameters in the assessment for *D. eleginoides* in Division 58.5.2 in 2021.

Model specifications	**Specifications**
Assessment period	1982–2021
Age classes	1–35 y
Length classes	300–2000 mm
B_0	Estimated
Mean recruitment R_0	Derived from B_0
Period of estimated *YCS*	1986–2015
σ_R for projections	Calculated from *YCS* 1992–2015

Estimated parameters	**Specifications**
B_0	Prior: uniform
Starting value (bounds)	90 000 (30 000–250 000)
Survey *q*	Prior: uniform-log
Starting value (bounds)	1 (0.1–1.5)
YCS	Prior: lognormal
Starting value (bounds)	μ = 1 (0.001–200), CV = 0.6
Fishing selectivities:	
Double-normal:	Prior: uniform
Sub-fisheries	Survey, Trawl1, Trawl2, LL1, LL2
Starting values (bounds)	a_1: 4 (1–20)
	σ_L: 1 (0.1–20)
	σ_R: 7 (0.1–20)
Double plateau normal:	Prior: uniform
Sub-fisheries	Trap
Starting values (bounds)	a_1: 10 (1–20)
	a_2: 6 (0.1–20)
	σ_L: 1 (0.1–20)
	σ_R: 3 (0.1–20)
	a_{max}: 1 (1–1)
Number of parameters	51

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Additional Resources

- Fishery Summary: pdf, html
- Fishery Report: pdf, html
- Species Description: pdf, html
- Stock Assessment Report: pdf
- Fisheries Documents Browser