Stock assessment of black teatfish (*Holothuria whitmaei*) in Queensland, Australia

2021

Queensland Government

This publication has been compiled by F. Helidoniotis of Fisheries Queensland, Department of Agriculture and Fisheries.

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Summary

Black teatfish (*Holothuria whitmaei* formerly *Holothuria nobilis*) is a species of sea cucumber found in the Indian Ocean and western Pacific Ocean (Purcell et al. 2012). In Australia, the distribution extends from Western Australia to Queensland. Black teatfish commonly inhabits coral reef habitats being most dense on reef flats, although they also occur on back slopes and reef fronts (Welch n.d.) in 0 to 30 m water depth. Female black teatfish mature at around 4 years of age at a length of 260 mm (TL) (Skewes et al. 2014). Individuals live to about 5–10 years of age and reach a maximum size of 560 mm (TL) (Skewes et al. 2014).

Records of fishing for sea cucumber in Queensland commenced in 1878 making it one of the oldest fisheries in Queensland (Uthicke et al. 2004a) (Figure 1). More recently, the Queensland Sea Cucumber Fishery (East Coast) was established during 1996, under the Queensland *Fisheries Act 1994*.

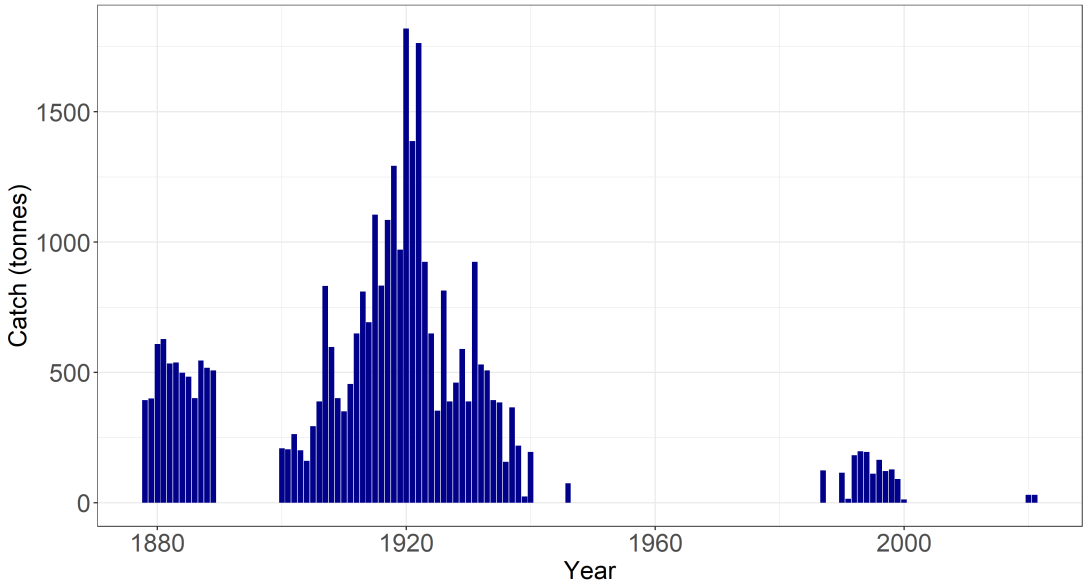

Figure 1: Total annual estimated catch of black teatfish in Queensland from 1887 to 2021

Black teatfish was listed under Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora, coming into effect during 2020. As a party to the Convention, the Australian government placed conditions on black teatfish Wildlife Trade Operation that included Condition 6: "By 30 September 2021, the Queensland Department of Agriculture and Fisheries must complete and publish stock assessment(s) for the Black Teatfish (*Holothuria whitmaei*) and White Teatfish (*H.fuscogilva*) in the Queensland Sea Cucumber Fishery (East Coast). The stock assessment for black teatfish must be based on the results of the survey undertaken as part of Condition 4."

The report herein presents the quantitative stock assessment for black teatfish that uses in part the results of the fishery independent biomass survey undertaken for Condition 4 of the WTO by Koopman et al. (2021).

The model used to assess the stock was an age-structured surplus production model with annual time steps. The key population performance indicator was an annual estimate of relative total biomass and relative exploitable biomass.

The assessment model incorporated historical catch data, published estimates of key biological parameters and was fitted to published model estimates of biomass (Skewes et al. 2014). Results from a random stratified survey in 2021 (Koopman et al. 2021) were used to estimate the biomass ratio in 2021 relative to that estimated by the model in 1877. The ratio was 40 to 42% (Figure 2).

The fishery independent biomass survey was undertaken in certain defined habitats of only the southern region (Zone 2, south of 19° S) of the Queensland fishery and therefore under-represents the total biomass across the geographic range of black teatfish in Queensland. In addition the survey does not include cryptic or semi-cryptic individuals, and these size classes might not have been represented in the biomass results. Therefore it is likely that the biomass in 2021, relative to 1877, is greater than 40–42% determined by the assessment (Table 1).

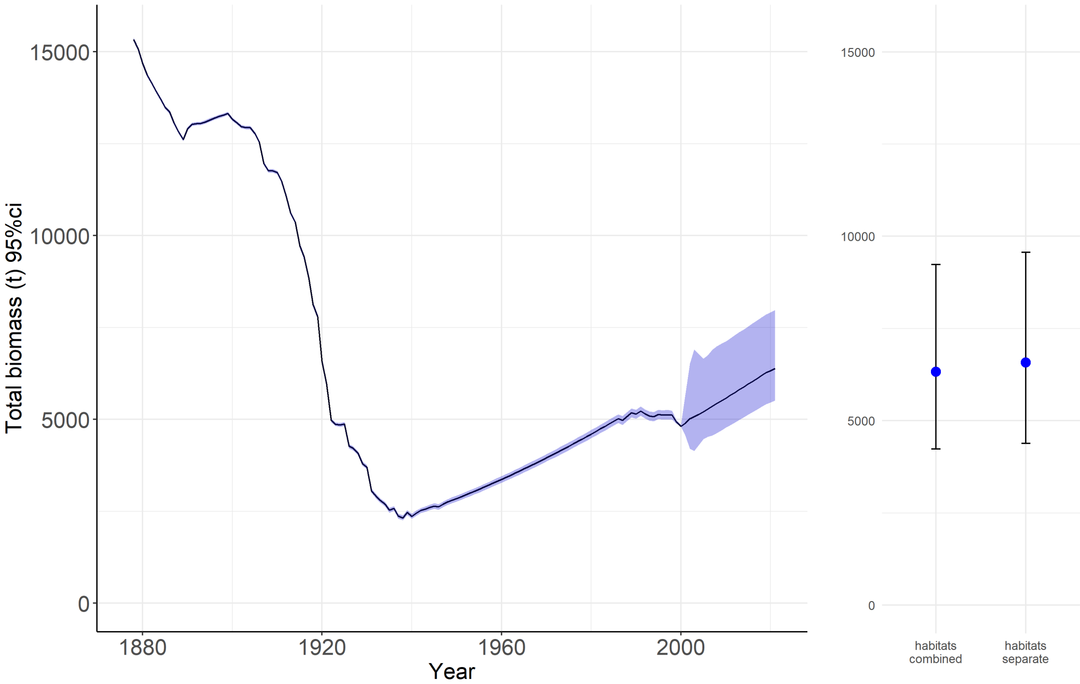

Figure 2: Total biomass of black teatfish in Queensland (with 95% confidence intervals) throughout the historical timeframe of the fishery from 1877 to 2021 and survey results by Koopman et al. (2021)

Table 1: Current and target indicators

Parameter	Estimate
Current total biomass (relative to 1877, $TotalB_{2021\ survey}/TotalB_{1877\ model}$) based on survey	40–42%
Current harvest (2021)	30 t

Acknowledgements

The project was supported by the Queensland Department of Agriculture and Fisheries. The author would like to thank the participants in the project team which consisted of the following Fisheries Queensland scientists and managers: Sian Breen, Carlie Heaven, Sue Helmke, Eddie Jebreen, Peter Kind, Samantha Miller, Alice Pidd and Anthony Roelofs. Particular thanks to the external scientist Dr Ian Knuckey for constructive critiques and discussions. Dr Alex Campbell and Dr Michael O'Neill provided useful advice and their technical expertise towards improving the model. Valuable feedback on model inputs were provided by members of the sea cucumber fishing industry. Tu Nguyen, Fisheries Queensland, is thanked for providing data on the GIS layer of sea-cucumber rotational zones.

Glossary

aspm	age-structured production model
available biomass	the sum of the biomass multiplied by selectivity in areas open to fishing (also available exploitable biomass)
CFISH	Queensland commercial fishery information system (logbook database)
DAF	Department of Agriculture and Fisheries (Queensland)
exploitable biomass, ExB	the sum of the biomass multiplied by selectivity
fishing year	fishing season from 1 July to 30 June, the labelling of fishing year is based on the second year e.g July 2000 to June 2001 was labelled '2001 fishing year', this applies to catches from 1996 onwards
year	fishing season of calendar year between 1877 to 1996 and fishing year after 1996
FRDC	Fisheries Research and Development Corporation
GBRMP	Great Barrier Reef Marine Park
MLS	minimum legal size
RAP	Representative Areas Program
SpB	spawning biomass
TACC	Total allowable commercial catch
total biomass, $TotalB$	the sum of the biomass of all individuals age 0 and above
TL	total length
WTO	Wildlife Trade Operations
Zone 1	zone located north of 19° S
Zone 2	zone located south of 19° S

1 Introduction

Black teatfish (*Holothuria whitmaei* formerly *H. nobilis*) is a species of sea cucumber found in the Indian Ocean and western Pacific Ocean (Purcell et al. 2012). In Australia, the distribution extends from Western Australia to Queensland. Black teatfish commonly inhabits coral reef habitats and are most dense on reef flats although also occur on back slopes and reef fronts (Welch n.d.) in 0 to 30 m water depth. Generally, the deep, sandy non-reef habitat is not considered a preferred habitat of black teatfish (Koopman et al. 2021). Female black teatfish mature at around 4 years of age at a length of 260 mm (TL) (Skewes et al. 2014). Individuals live to about 5–10 years of age and reach a maximum size of 560 mm (TL) (Skewes et al. 2014).

Fishing for sea cucumber in Queensland forms one of Australia's oldest fisheries. Commercial harvesting began in the early 1800s and continued with periods of interruption during the world wars and then after WWII until the mid 1980s. Fishing recommenced in the mid 1980s and the Queensland Sea Cucumber Fishery (East Coast) was formally recognised in 1996, under the Queensland *Fisheries Act 1994* and coincident with the introduction of the first logbook in 1995 (Table 1). The commercial fishery uses hand collection with underwater breathing apparatus to collect various sea cucumber species. The hand collection method is highly selective, resulting in minimal risk to non-target species. The fishery extends from the tip of Cape York to the southern limit of Tin Can Bay including parts of the Great Barrier Reef Marine Park (GBRMP). Management in Queensland applies a range of input controls including catch limits, limited entry, and spatial closures associated with fishery management as well as broader management of the GBRMP (Table 1). Since 2004, a rotational harvest strategy was introduced in the fishery to distribute the catches spatially. In addition to black teatfish, five other species of sea cucumber are targeted in the Queensland Sea Cucumber Fishery (East Coast) fishery. Other target species include burrowing blackfish, white teatfish, prickly redfish, sandfish and blackfish. Recreational harvest of black teatfish is not permitted in Queensland. This report focuses on black teatfish only.

Historically the fishery focused effort on black teatfish because it is the most commercially valuable species. It was more commonly fished north of 19° S (north of Townsville) than in the southern areas (Benzie et al. 2003). Observations by industry members, however, suggest large populations of black teatfish in deeper waters (15–20 m) (Koopman et al. 2021).

From 1 July 2004 to 1 July 2014, the fishery was divided into northern (Zone 1) and southern (Zone 2) management areas, split at latitude 19° S (Figure 2.2). The boundary, was established at the request of industry to promote collection of white teatfish south of the traditionally targeted areas located north of Townsville. The boundary commenced at the same time as the Rotational Zoning Scheme in 2004. Queensland Department of Agriculture and Fisheries removed the boundary between Zone 1 and Zone 2 on 1 July 2014 as there were no scientific, biological or management reasons to maintain the division. Zone 1 and Zone 2 are referred to in the 2015 and 2021 black teatfish surveys (Knuckey et al. 2016; Koopman et al. 2021) in reference to this historical split in fishing areas, however the zones do not exist in the current management arrangements for the fishery.

Table 1.1: Management changes applied to black teatfish in the Queensland Sea Cucumber Fishery (East Coast)

Year	Fisheries management, regulations and operations
1988	Compulsory commercial catch logbook reporting commenced
1991	Introduction of quota
1995	Introduction of logbook version BD01; number and weight required
1997–1998	Total allowable commercial catch (TACC) of 500 t for all sea cucumber
1998–1999	TACC black teatfish is 188 t
October 1999	Fishing for black teatfish closed
July 2000	Introduction of logbook version BD02; reports numbers of sea cucumbers (however other reports state that only weight required). Logbooks: improved species differentiation among 'other species' Fishing for black teatfish closed
2003–04	Introduction of Zone 1 (north of 19° S) and Zone 2 (south of 19° S)
2004	Rotational Zoning plan introduced (now Rotational Harvest Arrangement), effort managed by a Vessel Monitoring System but not recorded in logbook until 2009 RAP 1 July: Representative Areas Program (RAP) introduced, comprehensive rezoning of the whole Great Barrier Reef protecting a total of 37% of the fishable habitat in the GBRMP
July 2006	Introduction of logbook version BD03; only numbers of sea cucumbers required (weights recorded on buyer return logbook), improved species differentiation among 'other species'.
July 2009	Fishers to report rotational zone
July 2011	New conversion rate for quota
November 2013	Introduction of logbook version BD04, now reports weights instead of individuals
2019–20	Fishing for black teatfish reopened TACC black teatfish is 28.6 t
September 2021	Introduction of logbook version BD05 Commercial Logbook to be implemented to report estimated weights and number of containers

Previous surveys conducted during the early 2000s estimated the population densities and biomass in open and closed reefs (Uthicke et al. 2001; Benzie et al. 2003; Uthicke et al. 2004a). These surveys were used to inform a stock assessment model as part of a management strategy evaluation by Skewes et al. (2014). Based on the surplus production model, Skewes et al. (2014) suggested the spawning biomass in 2011 was approximately 80% relative to 1995 levels (2839 t in 2011, compared to 3549 t in 1995).

The surveys by Uthicke et al. (2001), Benzie et al. (2003), and Uthicke et al. (2004a), consisted of latitudinal studies comparing populations in different areas at the same point in time rather than changes over time. A survey in Zone 1 estimated that densities of black teatfish in open areas were 75% lower than those in reefs that had been closed to fishing within the same area (Uthicke et al. 2001). Benzie et al. (2003) reported that there was 5600 tonnes in protected areas (implying unfished biomass) and 2518 tonnes in open areas (implying biomass ratio of 44% in 1999). Following 15 years of a zero total allowable commercial catch (TACC) for black teatfish, a random stratified survey by Knuckey et al. (2016) estimated that densities of black teatfish in open areas of Zone 1 had recovered to 87.2–92.2% of those in reefs that had been closed to fishing. Surveys in Zone 2 were conducted more recently in 2021 by Koopman et al. (2021) and estimated that the median biomass in Zone 2 was 6327–6573 tonnes and included both open and closed areas (Koopman et al. 2021).

Based on the surplus production model, Skewes et al. (2014) suggested the spawning biomass in 2011 was approximately 80% relative to 1995 levels (2839 t in 2011, compared to 3549 t in 1995).

The purpose of this report is fulfill condition 6 of the application for approval of a Wildlife Trade Operation (WTO) to export under the EPBC Act (Environment Protection and Biodiversity Conservation Act 1999 and https://www.environment.gov.au/biodiversity/wildlife-trade/commercial/operations). Condition 6 of the WTO application states that: “By 30 September 2021, the Queensland Department of Agriculture and Fisheries must complete and publish stock assessment(s) for the Black Teatfish (*Holothuria whitmaei*) and White Teatfish (*H.fuscogilva*) in the Queensland Sea Cucumber Fishery (East Coast). The stock assessment for Black Teatfish must be based on the results of the survey undertaken as part of Condition 4.”

The report herein presents the stock assessment for black teatfish based upon the quantitative stock assessment and the results of the survey by Koopman et al. (2021). The model used to assess the stock was a surplus production model similar to that used in the management strategy evaluation in 2014 (Skewes et al. 2014) with annual time steps. The key population performance indicator was an annual estimate of biomass (total biomass and exploitable biomass). The model is applied to the Queensland east coast, open and closed areas, over the historical to present day fishery (1877–2021). An assessment of the stock, in terms of biomass ratio in 2021, was based on the biomass results of the survey from Condition 4 of the WTO (Koopman et al. 2021).

2 Methods

There is a single management region for black teatfish within the Queensland Sea Cucumber Fishery (East Coast) (Figure 2.1). Previously the fishery was divided in to Zone 1 and Zone 2 and currently the Rotational Harvest Program is in place to distribute effort in the fishery (Figure 2.2)

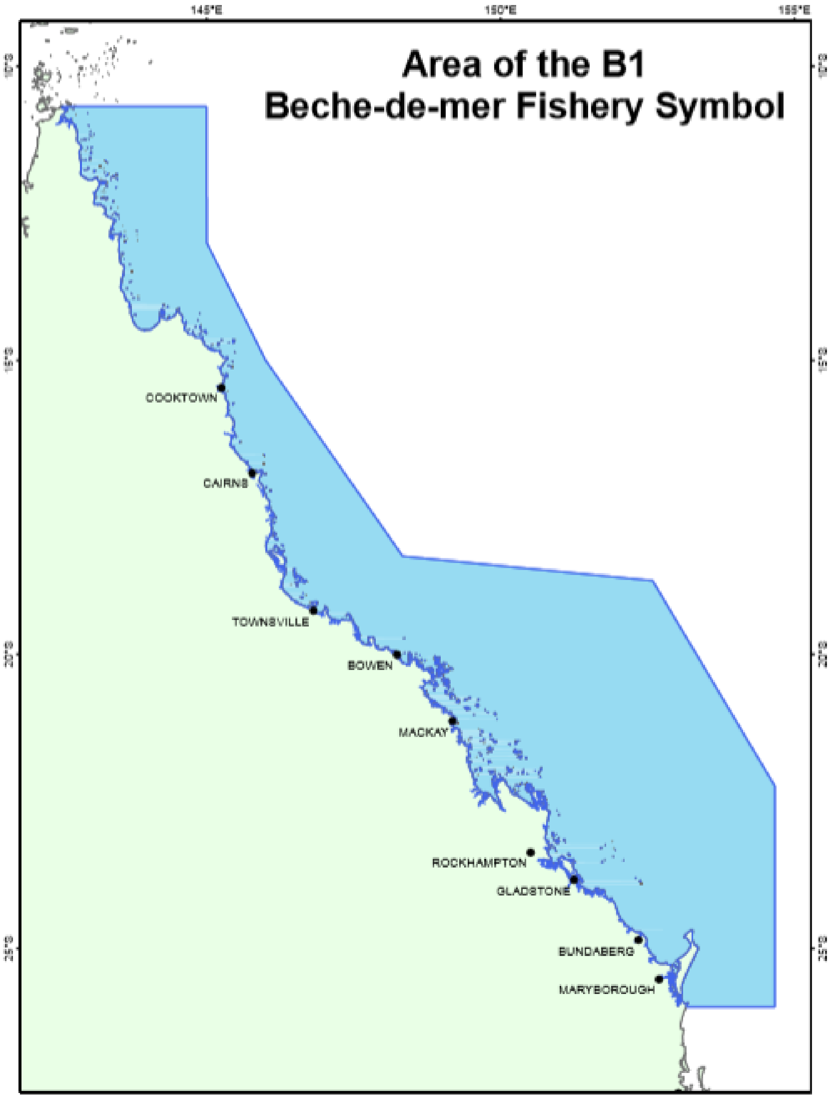

Figure 2.1: Area of the Queensland Sea Cucumber Fishery (East Coast).

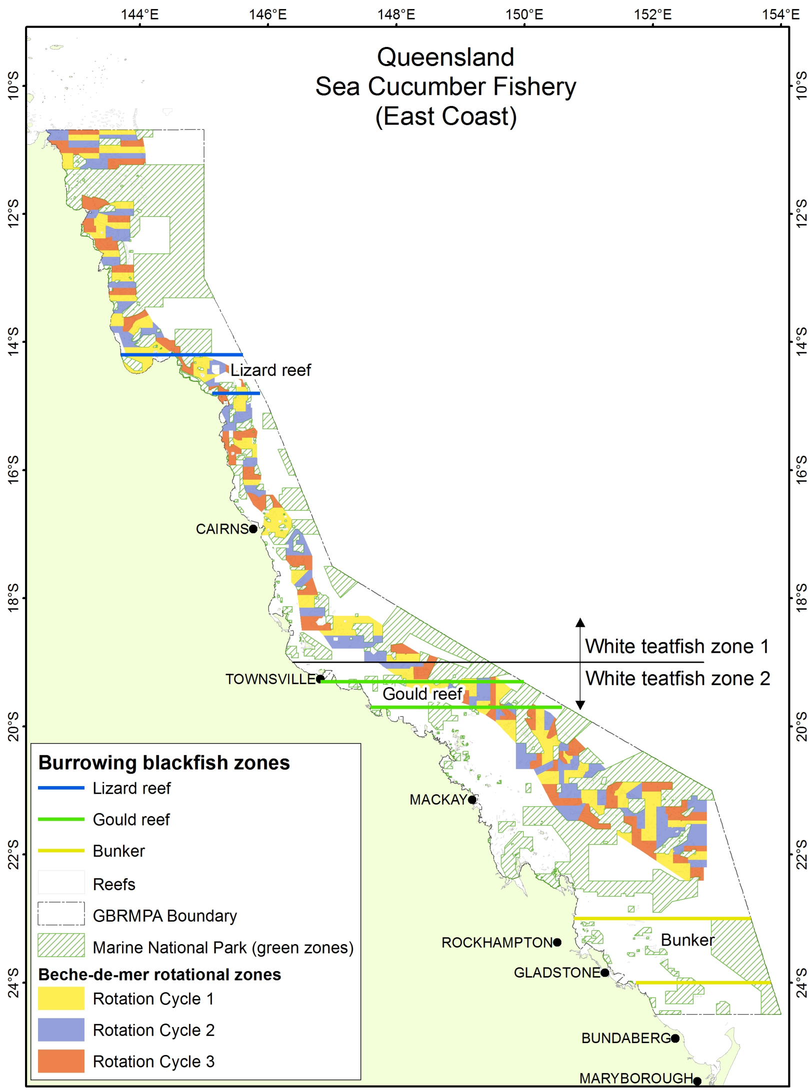

Figure 2.2: Map of the broadscale zones (no longer current) and the finer scale rotational zones in the Queensland Sea Cucumber Fishery (East Coast)

To fulfill WTO condition 6, the model was used in combination with the survey results of Koopman et al. (2021) to assess the stock in Queensland (Table 2.1). The model and survey results includes areas open and closed to fishing. It is to be noted that the model is Queensland wide between 26° S and 10° S but the survey results are for Zone 2. This spatial scale difference between the model and the survey were taken into account when assessing the stock.

2.1 Data sources

Various data sources were used in this assessment to determine total annual catch. The time series of annual historical catch was 143 years, from 1878 to 2021, noting the interruptions to catches during the world wars, the perceived absence of fishing after WWII and the closure of the fishery between October 1999–2020. For the present day fishery the fishing season is from 1 July to 30 June, and this is termed 'fishing year'. The labelling of fishing year is based upon the second year e.g July 2000 to June 2001 was labelled '2001 fishing year'

For historical catches, from 1878 to 1996, the fishing season is assumed to be a calendar year. Henceforth the term 'year' was be used to denote either calendar year or fishing year.

The full time series of historic catches (between 1878 and 2021) consists of three sources (Table 2.1):

- historic catches between 1878 and 1996 based on an FAO report, and
- a further two sources of catches between 1996 and 2021:
  - one source from the commercial logbook records and
  - another source from the buyer logbook records.

Table 2.1: Data compiled for input into the population model

Type	Year	Source
Historical catch records	1878–1996	FAO report. (Uthicke et al. 2004a)
Torres Strait catch	1996–1999	AFMA report. (Uthicke et al. 2004a)
Commercial vessel data	1996–2021	Commercial logbook data collected by Fisheries Queensland. Data extracted 1/4/2021
Commercial buyer data	2001–2021	Buyer logbook data collected by Fisheries Queensland
Fishery independent survey data for the area below 19° S (Zone 2)	2021	Koopman et al. (2021)
Biomass (Queensland wide)	1996–1999	Skewes et al. (2014)

Commercial catch and effort data were sourced from the Fisheries Queensland compulsory logbook records (CFISH), which began in 1996. The Queensland data contained daily entries for each boat for harvest in kilograms and the geographic location (latitude and longitude) within the sea cucumber fishery (Table 2.1) allowing fine scale spatial distribution of fishing effort to be determined.

2.2 Harvest estimates

Logbook records were analysed and identified as the same operation date and end date of fishing. Data were grouped by vessel and operation date to generate daily harvests for black teatfish. The data from commercial vessel logbook records were considered to under-represent the actual catch whereas the buyer data were considered more accurate (Figure 2.3). The commercial data have been recorded for 7 years (discontinuous due to closure of the fishery between 1999–2020) whereas the buyer data were recorded for 2 years (2020–2021). There were differences in features between the two sources. Commercial records offered the longest time series (longevity) while the buyer data offered more accuracy. In order to combine the two features of longevity and accuracy, the harvest data were reconstructed from buyer records and commercial logbook records. This was achieved by adjusting the commercial records to match the buyer records for the years with no buyer data and then using the buyer data henceforth. Details as follows:

- Calculate the mean of the difference over the overlapping years (2020–2021), which was 0.084
- For 2020–2021, data compiled from commercial buyer records
- For 1996–2000, catch adjusted from commercial records using the following equation: commercial catch × (1 + mean of the difference)

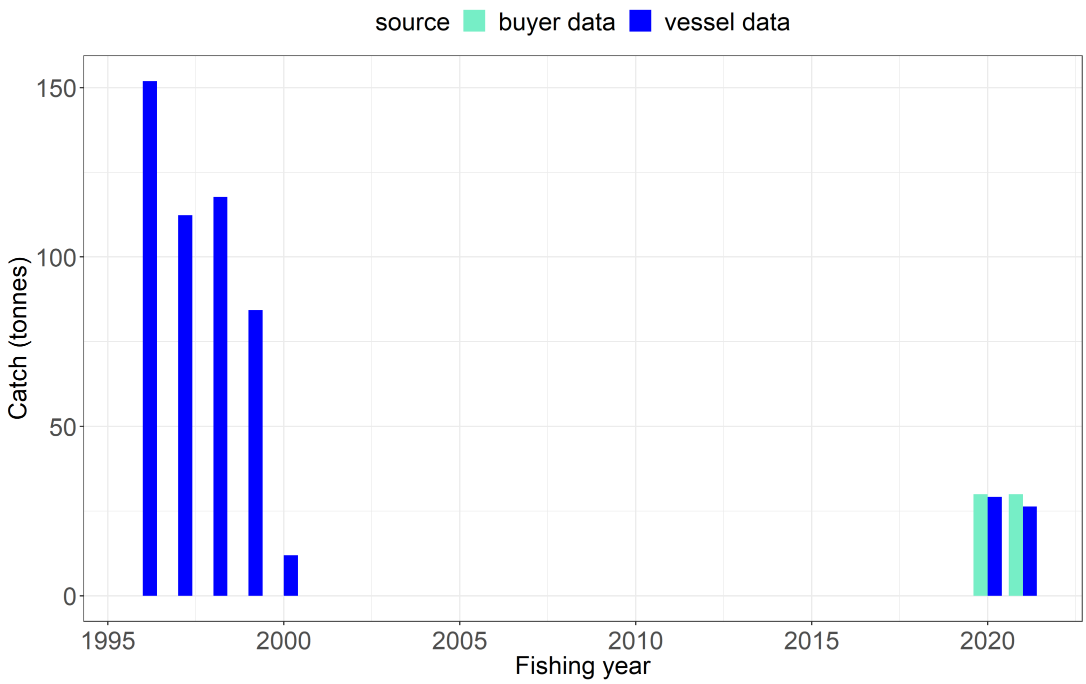

Figure 2.3: Catches recorded in the commercial buyer and commercial logbook data for black teatfish in the Queensland Sea Cucumber Fishery (East Coast)

Harvest data from 1878 were assumed, for modelling purposes, to represent the commencement of significant fishing mortality followed by a long period (approximately 40 years) of no catches. Historical catches were published for sea cucumber in Uthicke et al. (2004a). However these included catches of all sea cucumber (not just black teatfish) from Queensland and other regions, mainly Torres Strait (AFMA 2008). Therefore the published historical catches needed to be adjusted to best account for black teatfish in Queensland only. The reconstructed historical catch formed an input into the model. The method used to adjust the historical catch was as follows:

- Calculate the mean proportional difference between CFISH logbook catches and published catches (Uthicke et al. 2004a) for the years in common (1996–2000), which was 0.53 (Figure 2.4).
- Calculate the mean proportional difference the CFISH logbook catches and the sum of the Torres Strait catches and Queensland (CFISH) logbook catches for the years in common (1996–1999), which was 0.6 (Figure 2.5)

Due to the different reporting between the historical data and the logbook data, the term ‘Year’ in this assessment was calendar years prior to 1996 and financial or fishing year after 1996. There was only one year (the cusp year 1996) that would have been affected by slightly extra catches, however this was inconsequential to the results.

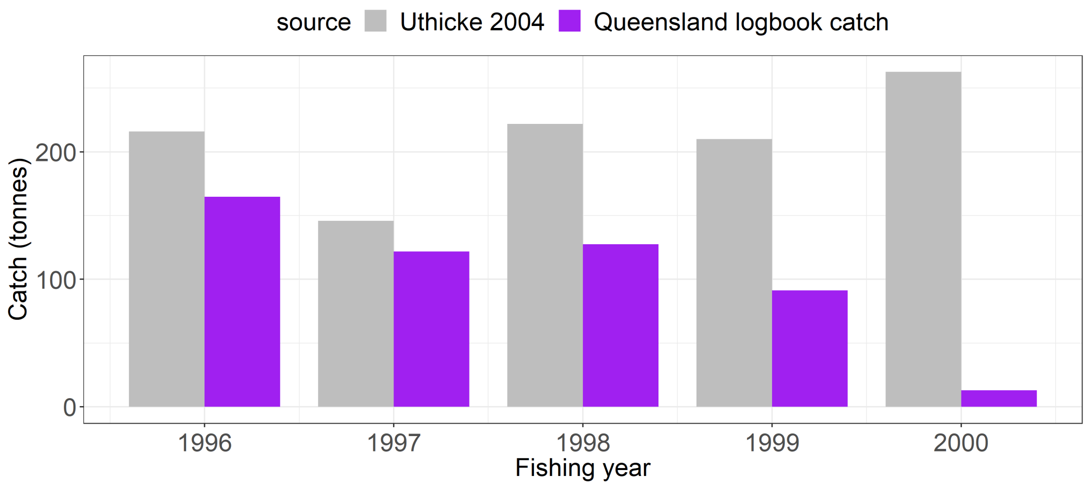

Figure 2.4: Annual catch of black teatfish reported by Uthicke et al. (2004a) and logbook catches for the Queensland Sea Cucumber Fishery (East Coast) from 1996 to 2000

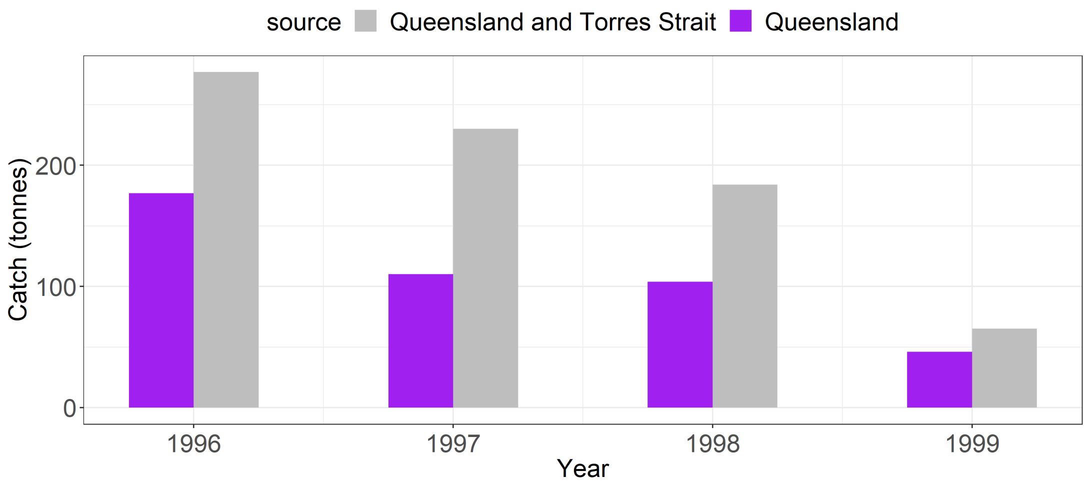

Figure 2.5: Annual catch of black teatfish in the Torres Strait and the Queensland Sea Cucumber Fishery (East Coast) from 1996 to 1999

Historical catches were based on catches reported for sea cucumber in Uthicke et al. (2004a) and were adjusted to best account for black teatfish in Queensland only. To account for uncertainty in the reconstruction of historical catches, two harvest reconstructions were developed: one as a base case (Figure 3.1) and another as a scenario (Appendix A). The resulting reconstructed historical catches are described in Table 2.2

Table 2.2: A description of the scenarios used for the model

Model	Description
Base case	53% of Uthicke et al. (2004a) between 1987 and 1995 (inclusive) and 32% of Uthicke et al. (2004a) before 1987 (0.32×53)
Alternate scenario	53% of Uthicke et al. (2004a) for all years before 1996

The base case model was used to fulfill condition 6 of the WTO application and to also determine biomass ratio estimates. The outputs for the two model runs were also useful for addressing the sensitivity of the model outputs to two selected performance indicators: exploitable biomass in 2021 and total biomass in 2021 (compared to unfished levels in 1877). Sensitivity results are presented in the Appendix A.

2.3 Abundance indices

The biomass outputs from Skewes et al. (2014) were used as abundance indices to which the model was fitted.

2.4 Biological parameters

The relevant parameters values used in the assessment are shown in Table 2.3. The biological information and parameters relevant for the age-structured production model were similar to those used in the surplus production model of Skewes et al. (2014), with the exception of the steepness and natural mortality parameters.

The steepness parameter was obtained from a preliminary study on black teatfish (Helidoniotis in prep) that used an age-based surplus production model fitted to standardised catch rate data. The study was a separate assessment of black teatfish on the present day Queensland sea cucumber fishery (East Coast). The assessment used an age-based surplus production model, similar to the model used herein. The separate assessment was fitted to standardised catch rates and the best fitting parameters were obtained. The best fitting value for the steepness parameter was 0.22. This was quite low and unexpected, however other values were tested (ranging from 0.22 to 0.7) but led to poor fits.

Natural mortality was based on the method using Hoenig's formula (Hoenig 1983) based on life span (10 years for black teatfish). The growth parameters and length to weight parameters in the current assessment were additional parameters required for the age-structured production model.

2.4.1 Growth

Growth in mean body weight at age was a two-step process. Firstly, the von Bertalannfy age-at-length model was applied (Equation 2.1), then length was converted to weight using a length-to-weight equation (Equation 2.2). For black teatfish, the age a is defined in terms of year.

$$L_t = L_\infty(1 - \exp(-k(t - t_0))) \tag{2.1}$$

where L_t is the length at age t, L_∞ is the asymptotic maximum length, k is the growth coefficient, and t_0 is the time (age) at length zero. The parameter for L_∞ was 560 mm (total length), and the parameter for k was 0.5.

$$W_L = \alpha L^b \tag{2.2}$$

where W_L is weight to length, and α and β were 0.0003 and 2.55, respectively.

2.5 Population model

An age-structured surplus production model was used that operated on annual time steps. The model was selected from the FRDC toolbox and written by Haddon et al. (2019) (R package '*aspm*', age-structured production model, http://toolbox.frdc.com.au/). The current packaged model includes an option that consisted of two parameters (initial recruitment and standard deviation for catch rate).

Some adjustments were made to the prepackaged *aspm* model, by the addition of parameters, to improve the model fit and capture the uncertainty. The improvement in fit by the addition of parameters was explored for white teatfish (Helidoniotis 2021). When the original pre-packaged *aspm* model was applied, the results of the model fits between observed and predicted catch rate captured the overall large scale changes but not the fine scale interannual changes (Helidoniotis 2021). This represents the fishery dynamics very poorly. The model was reformulated slightly to include annual recruitment deviates, thus adding additional parameters and this improved the fit (Helidoniotis 2021). Adding too many parameters can introduce the problem of over-parameterisation. Nevertheless, the strategy of trying to improve on the original inadequate model fit is described in Helidoniotis (2021) and this describes the decision to include the extra parameters of recruitment deviates.

The results of the model fits between observed biomass estimates from Skewes et al. (2014) and predicted biomass were good with the exception of 1995 of Skewes et al. (2014) which was likely an estimate used to initiate the model.

2.5.1 Population dynamics

The dynamics of the age production model tracked numbers (N), biomass (B) and recruitment in every year (t) (Haddon et al. 2019). Total biomass was the biomass of age 0 and older animals after catch was applied. Exploitable biomass was the biomass of animals $>$ 300 mm (TL) (approximately 1.5 to 2 years of age) after catch was applied.

Recruitment numbers—Beverton-Holt formulation

Recruitment numbers (R) were assumed to follow an annual Beverton and Holt function with lognormal deviations. The model was firstly initialised to generate and unfished stock in equilibrium using virgin recruitment (R_0), estimated on the log scale using the parameter R_{init} (Equation 2.3). After the model was initialised, a series of equations were used to estimate annual recruitment numbers over the current time series of the fishery as follows:

- Estimate the number of female black teatfish spawning each year (S_y, Equation 2.6)
- Use steepness (h) and virgin recruitment (R_0) and the number of female spawners (S_y) to estimate α and β (Equation 2.7)
- Use α, β in the Beverton Holt stock recruitment equation to estimate annual recruitment (Equation 2.8)

$$R_0 = \exp\left(R_{\text{init}}\right) \times 10^8 \tag{2.3}$$

$$r_{\text{max}} = 1 + \exp\left(\xi\right) \tag{2.4}$$

$$h = r_{\text{max}}/(4 + r_{\text{max}}) \tag{2.5}$$

$$S_y = 0.5 \sum_{t=1}^{12} \theta \frac{1 - \exp(-Z_t)}{Z_t} N_t \tag{2.6}$$

$$\begin{aligned} \alpha &= \frac{S_0(1-h)}{4hR_0} \\ \beta &= \frac{5h-1}{4hR_0} \end{aligned} \tag{2.7}$$

The number of annual recruits from the Beverton-Holt equation was:

$$\text{rec}_y = \frac{S_y}{\alpha + \beta S_y} \tag{2.8}$$

Recruitment deviates were estimated from 1996 to 2021 to obtain variation in the biomass. For the assessment model, the original *aspm* model was used (Haddon et al. 2019) and no extra parameters for recruitment deviates were formulated.

Harvest rate

In the population model, harvest rate was used instead of instantaneous fishing mortality, to account for time-varying fishing mortality (Hilborn et al. 1992) and is the observed catch divided by predicted exploitable biomass (Equation 2.9):

$$u_t = C_t / B_t \tag{2.9}$$

where C_t is the annual catch (t) and B_t is the predicted annual exploitable biomass.

2.5.2 Model assumptions

The main assumptions of the model were as follows:

- Growth in mean body length at age is described by a von Bertanffy equation.
- All animals aged r and older are equally vulnerable to fishing, implying knife-edged selectivity at age r.
- All animals aged 0 and older have the same annual natural mortality rate.
- All animals aged r and older have the same catchability.
- Catch rates were proportional to abundance.
- Mean growth function for weight was applied over both sexes combined.
- A common steepness was applicable to the whole population.

Other assumptions include the size range of the total biomass. Total biomass in the model is all individuals greater than 0 year old however the survey by Koopman et al. (2021) excluded very small animals. However for the purposes of this report total biomass from the survey is assumed to represent equal size distributions.

2.5.3 Model parameters

Table 2.3: Fishery constants and biological parameters used in the revised age-based surplus production model

Parameter	Value	Fixed/ estimated	Description
Fishery constants			
start year	1878	fixed	commencement of catches (Uthicke et al. 2004a)
end year	2021	fixed	Final year of data
recfishyr	24	estimated	Number of years of recruitment deviations (1996–2021) in the model
rec_fyr	1996	fixed	First year to estimate recruitment deviations
Natural mortality			
M	0.5	fixed	One parameter for instantaneous natural mortality per year
Recruitment			
R_{init}	1	estimated	Used to determine R_0 (Equation 2.3)
R_0 scaler	10^7	fixed	Scaler for R_0
ζ	mean $= 0$, sd $= 0.5$ to 0.8	estimated	24 recruitment deviates, normal random, for n recruitment years (see recfishyr)
Stock recruitment			
steepness	0.22	fixed	Beverton-Holt steepness (h) for age-structured model (Helidoniotis in prep)
Length-to-weight			
alpha	0.0003	fixed	Average weight (g) at length l (divide by 1000 for kg)
beta	2.55	fixed	See Equation 2.2
Other parameters			
maxAge	10	fixed	Maximum age
L_{inf}	560	fixed	Maximum length for von Bertalannfy growth model (Skewes et al. 2014)
W_{inf}	3	3	Maximum weight (kg)
k	0.5	fixed	For von Bertalannfy growth model
t_0	0.66	fixed	For von Bertalannfy growth model
SM_{50}	260 mm	fixed	Size at maturity (TL) (Skewes et al. 2014)
deltaM	50	fixed	The difference in size between the age at 50% and the age at 95% maturity
R_0	11	fixed	Average recruitment of the unfished stock
MLS	300	fixed	Minimum Legal size and fishing selectivity (knife edge)
deltaS	11.69	fixed	The difference in length between the age at 50% and the age at 95% selectivity
resilience	low	fixed	Population resiliance for age-structured model
number of ages	10	fixed	For the age-structured model

Table 2.4: Comparison of fishery constants and biological parameters with Skewes et al. (2014)

Parameter	Value	Skewes et al. (2014)	Definition
M (year^{-1})	0.5	0.3–0.6	Natural mortality
steepness	0.22	0.5–0.7	Stock recruitment
W_{inf}	3	3	Maximum weight (kg)
L_{inf}	560	560	Maximum length (mm TL)
maxAge	10	5–10	Maximum age, no plus group
SM_{50}	260 mm	260 mm	Size where 50% of population reach maturity
MLS	300	300	Minimum legal size and fishing selectivity (knife-edge)

2.6 Biomass ratio

As a requirement of the WTO condition an assessment was conducted on black teatfish. The stock assessment estimated total biomass and exploitable biomass. The total biomass ratio in 2021 was based on the fishery independent survey results from Koopman et al. (2021) in Zone 2. The biomass ratio in 2021 was obtained by dividing the fishery independent survey results by the starting biomass in 1877 estimated by the stock assessment model. The exploitable biomass ratio was based wholly on the outputs of assessment model

3 Results

3.1 Model inputs

3.1.1 Harvest estimates

Published reports indicate that fishing began in 1878, Uthicke et al. (2004a). Since the early 1800s, commercial harvesting continued with periods of interruption during the world wars and then after WWII until the mid 1980s. Fishing recommenced in the mid 1980s and harvest data from 1986 represents recommencement of significant fishing mortality following about four decades of no catches. The Queensland Sea Cucumber Fishery (East Coast) was formally recognised in 1996, under the Queensland *Fisheries Act 1994* and coincident with the introduction of the first logbook in 1995 (Table 1). The catch remained stable at 30 tonnes since 2020 due to the TACC quota applied by management.

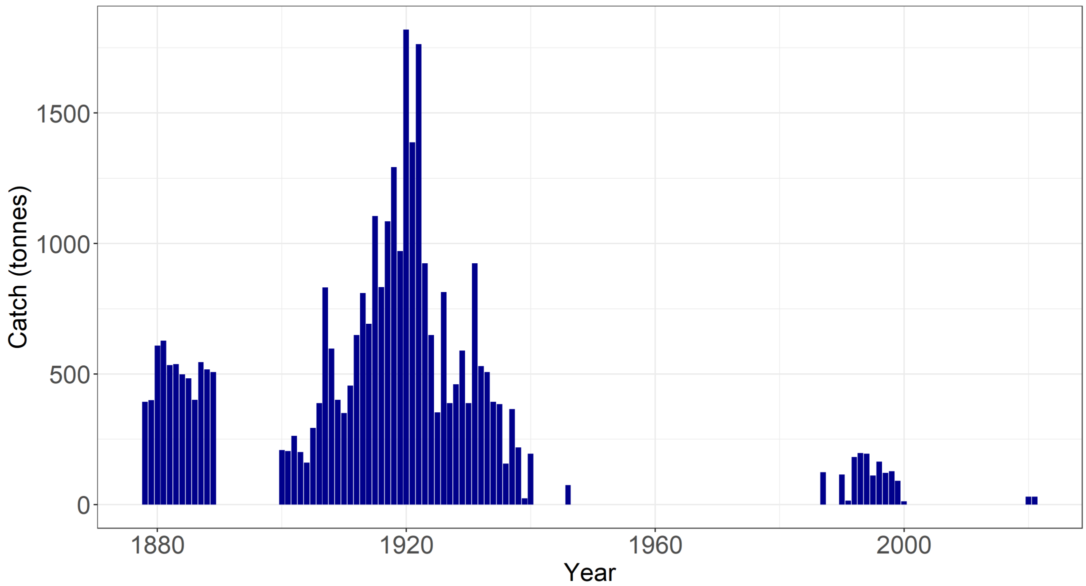

Figure 3.1: Total annual estimated catch of black teatfish in Queensland from 1887 to 2021

3.2 Model outputs

Model outputs were informed by input data from annual harvests, biomass by Skewes et al. (2014) and by fixed and estimated model parameters (Table 2.3).

3.2.1 Model parameters

There were 25 parameters estimated by the model including 24 for annual recruitment and one for initial recruitment (R_{init}). The fitted parameter value for (R_{init}) is 16.359 (with a 95% confidence interval of 16.357–16.363).

3.2.2 Model fits

The model was fitted to biomass estimates from the Skewes et al. (2014) (Figure 3.2). The estimated biomass from the model fitted the data reasonably well with the exception on the biomass in 1995 which was probably used to initiate the model in Skewes et al. (2014).

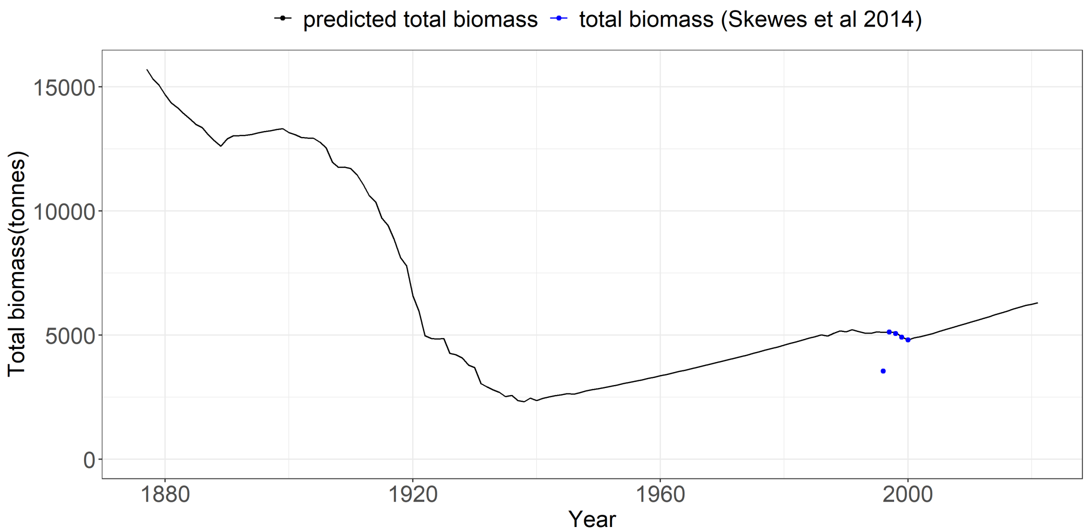

Figure 3.2: Observed (black) and predicted (blue) total biomass for black teatfish in Queensland fitted to biomass results from Skewes et al. (2014)

3.2.3 Biomass

The survey estimated that the median biomass in Zone 2 was 6327 and 6573 tonnes (for 'habitats-combined' and 'habitats-separate', respectively). Habitats-combined was based on the analysis of reef top and deep reef data combined. Habitats-separate was based on analysis of reef top and deep reef data as separate strata (Koopman et al. 2021). The starting biomass in 1877, according to the stock assessment model, was 15 709 tonnes. The biomass ratio in 2021 was obtained by dividing the survey results by the starting biomass. This resulted in a total biomass ratio of 40–42% in 2021. It is to be noted that the survey included both open and closed areas in Zone 2 only (Koopman et al. 2021), and the model included all of Queensland east coast waters within the area of the B1 symbol shown on Figure 2.1. Therefore the ratio may be higher.

The model also estimated exploitable biomass. It is presented as a ratio relative to 1877 that was estimated from the best fitted parameters. The exploitable biomass ratio in 2021 was 40% relative to 1877 (Figure 3.3). Over the historical time period, the exploitable biomass ratio declined to 14% in 1938 and has steadily increased since the 1940s (Figure 3.3). Although the stock recovered, the rate of recovery was quite slow.

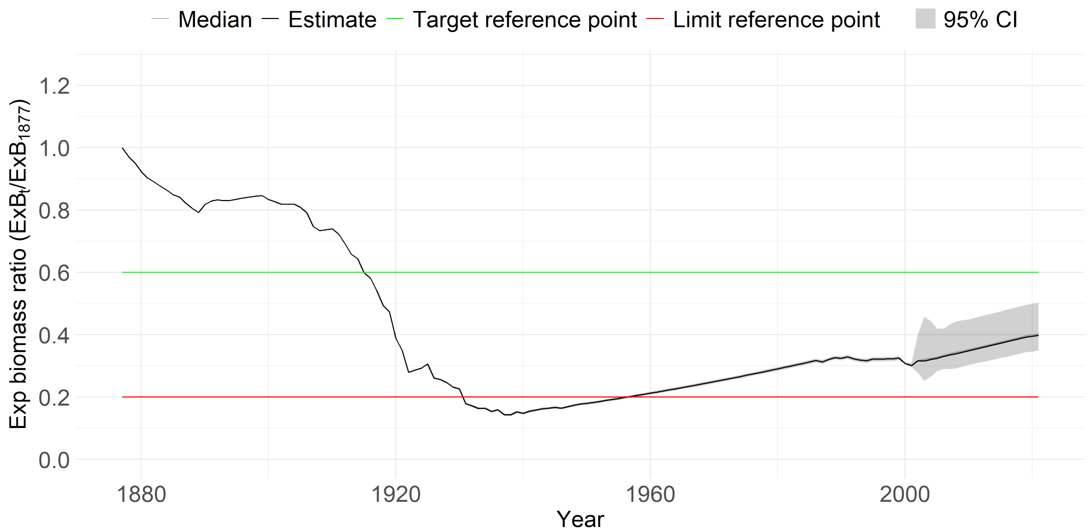

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Figure 3.3: Annual exploitable biomass for black teatfish in Queensland and 95% confidence intervals for the base case model

4 Discussion

4.1 Biomass

The total biomass in 2021 in Zone 2, as estimated by the black teatfish fishery independent survey, was between 6327 and 6573 tonnes for habitats-combined and habitats-separate. The survey included areas that are open and closed to the present day fishery. The TACC for the fishery is limited to 30 tonnes and based on the survey, the population in Queensland would be stable at this level of catch. In addition, to protect commercial sea cucumber stocks from unsustainable fishing pressure, rotational management was introduced in 2004. Rotational closures have also been implemented for sea cucumber in British Columbia, Canada (Perry et al. 1999)

The black teatfish biomass in Queensland as estimated by the model was 6310 tonnes in 2021 (this estimate encompasses the entire east coast of Queensland; encompassing both open and closed areas). Based on the results of the fishery independent survey, 2021 biomass ratio is estimated as 40–42% relative to 1877. It is to be noted that the model is Queensland-wide between 26° S and 10° S but the 2021 biomass survey was undertaken in Zone 2. Therefore the survey under-represents the total biomass across the geographic range of black teatfish in Queensland. In addition the survey does not include cryptic or semi-cryptic individuals, and these size classes might not have been represented in the total biomass results (which includes cryptic forms). Therefore it is likely that the biomass in 2021, relative to 1877, is greater than 40–42% as determined by the assessment.

The time series of catches began in 1878, which is a long time series. Long time series of catches are helpful and provide better estimates of productivity and information on how the stock responds to fishing pressure, however historical catches are uncertain. The high historical catches prior to 1950 appear to have led to fishery collapse.

Fishing was reported to have begun in 1878, Uthicke et al. (2004a). The harvest data from 1986 represent recommencement of significant recent fishing mortality following about four decades of no catches. Whilst it is likely that significant recovery occurred over this time, it is uncertain whether recovery to a virgin state would have occurred. Therefore to help explore this the unfished year (1877), the year prior to the first year of catches, was selected as start year for the model.

Across Queensland, the stock biomass has steadily increased since 2001 with a prolonged period of zero catch (2000–2019) and under the current harvest condition of a 30 t TACC, since the fishery was reopened in 2019. Although the stock recovered, the rate of recovery has been quite slow and this was also reported in Uthicke et al. (2004b). The rate of recovery was determined by the steepness parameter and this was obtained from a separate preliminary study yet to be published (Helidoniotis in prep). The preliminary study was a separate assessment of black teatfish on the present day Queensland sea cucumber fishery (East Coast) and used an age-based surplus production model, similar to the model used herein. The model was fitted to standardised catch rates and the best fit was achieved with a steepness of only 0.22, which implied a low rate of recovery.

Previously, a quantitative analysis was conducted in 2014, as part of a management strategy evaluation framework (Skewes et al. 2014). Although this was not intended as an assessment of the stock, it consisted of biomass simulations for black teatfish in Queensland. While it can be interesting to compare biomass ratios to those presented in Skewes et al. (2014), important caveats apply. Mainly, the start year for the model in Skewes et al. (2014) was 1995 whereas the start year in the assessment presented herein started in 1877. Skewes et al. (2014) suggest that the spawning biomass ratio in 2011 was approximately 80% relative to 1995 levels (estimated total biomass was 2839 t in 2011 and 3549 t in 1995). However results herein show recovery, and the spawning biomass ratio in 2011 was approximately 109% relative to 1995 levels. This may raise the question as to whether the current assessment overestimated biomass or whether Skewes et al. (2014) underestimated biomass over the time series.

The term 'exploitable biomass', requires further clarification on the accepted meaning of the term and the implication for sea cucumber stocks. Implicit in the definition of exploitable biomass is that the 'stock' (i.e that which is fished) is a dynamic pool (Quinn et al. 1999). 'Dynamic pool' is the idea that if a pool of individuals are removed, the effect is evenly distributed across the whole pool. This notion was derived from a consideration of mobile fish species. Under the assumption of a dynamic pool the exploitable biomass is equivalent to the available biomass and that is because there is assumed to be no spatial heterogeneity in a species' distribution. That approximation makes some sense for highly mobile free-swimming fish species however invertebrate species, such as sea cucumber, break the assumption of a dynamic pool. Often, spatially, sea cucumber stocks are made up of a collection of discrete sub-populations to form a meta-population (Perry et al. 1999). The dynamic pool assumption will not be valid for sedentary species with complex spatial distributions, unless the unit stock is defined at the scale of the local aggregation (Perry et al. 1999). Applying ideas about single populations to such meta-populations is risky. In this report the exploitable biomass refers to that portion of the biomass that is above a certain size in both open and closed areas. However this concept is risky for stocks that break the assumption of a dynamic pool as is the case for sea cucumber.

4.2 Performance of the population model

Analysis of standardised residuals indicated that the age-structured production model fitted the data from Skewes et al. (2014) reasonably well and that the assumed error structures were valid. However with only five years of fishery independent biomass data inputs, uncertainties are expected to be high. The predicted estimates of total biomass in 2021 were consistent with the survey results although slightly lower.

There are a number of key assumptions. Growth rates and natural mortality were assumed to be constant throughout the period. Other key assumptions are related to the recruitment aspects of stock dynamics and include:

- that the stock was in an equilibrium, unfished state in 1877
- that the Beverton-Holt stock recruitment relationship (with associated recruitment residual structure) provided an acceptable description of recruitment dynamics. That is, the equations were capable of capturing the biological recruitment dynamics as well as variations introduced by environmental factors, which may be influential.
- that all of the historical catches dating back to 1887 were above the minimum size of 300 mm, however it is likely that individuals below this size were caught.

4.3 Uncertainty

One source of observation uncertainty is historical catches. Historically the harvest before 1996 may be interpreted differently and subject to change in future assessments because there was uncertainty at the magnitude of the historical catches.

Another source of uncertainty is that the data on biomass from the surveys may not be comparable through time. Different authors used different methods and spatial scales, and this may have affected the outputs of the model. In addition, biomass survey data were only from a relatively small area and required extrapolation to the much larger area.

Model uncertainty and estimation uncertainty are another major source of uncertainty due to the little available data. The stock dynamics were informed by average recruitment during the majority of time series and by variable recruitment of biomass from only five biomass data inputs, from Skewes et al. (2014) over the 143 year time series. The availability of only five biomass estimates will contribute to estimation uncertainty. There is a long history of catches without any accompanying catch rate or biomass data and this may contribute to further uncertainty in the model. This along with many years of no catches gives rise to multiple interpretations of unfished biomass.

It is possible that the productivity of the stock has declined and has impaired rebuilding to the biomass levels observed in 1880s. Given sea cucumber live to 5–10 years, the period of no fishing should have afforded recovery. If there is any occurance of illegal, unreported and unregulated fishing in Queensland waters then these may undermine the fishing dynamics on which the model aims to capture.

The area fished historically may not be the same in the present day fishery. It seems likely that, if the fishery before 1950 caught more than 1500 t, the spatial extent of the historical fishery must have been greater than the present day fishery.

Interestingly, although Uthicke et al. (2004a) reported it was possible to extract over 1000 tonnes of catch for a few years around 1920, there seemed to be no recovery after approximately 40 years of no fishing after 1945. That raises the question of whether there is some form of depensation occurring where the stock becomes extremely low and remains low through reproductive failure. Depensation contributes to decreased recruitment levels. A biomass ratio above 30% will keep a stock from collapsing in a model containing depensation (Quinn et al. 1999). The biomass ratio black teatfish was below 30% for 60 years between 1922 and 1982 which is consistent with depensation occurring. The biomass ratio has remained above 30% since 1982 it seems less likely that depensation was occurring in recent years.

The accumulation of all the above mentioned uncertainties create challenges when generating a defensible biomass-based stock assessment model on the basis of the available data. However this report has revealed findings that may have challenged existing hypotheses especially regarding the notion that the stock should have fully recovered after 40 years of no fishing. The finding was based on estimates of biomass from as early as 1877, whereas previous notions were based on single year biomass surveys that compared open area to closed area without considering the closed area may have been previously fished and hence depleted.

4.4 Recommendations

Generally, it is recommended to identify the critical information gaps for sea cucumbers in Queensland. Research on sea cucumber fishery in British Columbia (Perry et al. 1999) identified the gaps in population structure, the spatial scales for sea cucumber migration and recruitment, and natural mortality.

In addition, Woodby et al. (1993) identifies the need of a conservative framework for modelling sea cucumber.

4.4.1 Data

Future analyses could consider if the historical time series of catches should be revised.

4.4.2 Monitoring

Information gaps exist in the stock structure of black teatfish in Queensland. Fishery independent studies can be applied to evaluate estimates of stock biomass in both open and closed areas. Surveys can also be developed to monitor exploitation rates and define stock structure. Further recommendations are described in Perry et al. (1999)

Updating the length-to-weight conversion formula by collecting length and weight data is generally considered to improve the robustness of the model. However collecting biological information is difficult for sea cucumbers (Perry et al. 1999); for example the inability to measure length or age as the body length varies through handling. This makes it difficult to provide the standard scientific assessment advice and the age-structure of the adult population can only be approximate. Therefore it is recommended that further and careful consideration be given when determining the best way to apply monitoring in future.

Temperature may affect the population biology of marine ectotherms. An updated collection of biological data such as growth and maturity may better inform the model parameters.

4.4.3 Assessment

It is recommended to develop a model that can incorporate catch and effort data from the fishery logbooks as an index of abundance to address the Queensland sea cucumber fishery harvest strategy. Initial work has commenced (Helidoniotis in prep) and model development will continue to progress and align with the strategy (State of Queensland 2020).

In addition, separating the results from the existing survey (Koopman et al. 2021) into open and closed areas will improve estimates of biomass for the area open to the fishery.

A further recommendation is to explore hyperstability in catch rates and reevaluate the catch rates according to Carruthers et al. (2011).

4.4.4 Management

Completion of a stock assessment is a key deliverable under the *Queensland sea cucumber fishery harvest strategy: 2021–2026* (State of Queensland 2020). The harvest strategy states “For tier 1 stocks, performance indicators and sustainable harvests for all sectors will be estimated using a stock assessment.” The harvest strategy also states “It is a priority under this harvest strategy to develop a modelled stock assessment for the commercial fishery area to inform the TAC-setting process.” Table 6 of the strategy (Information and research priorities) advises that white teatfish stock assessment is high priority, black teatfish stock assessment is high priority and burrowing blackfish stock assessment is moderate priority.

As noted above, the limitations on data inputs to this assessment have resulted in a number of uncertainties that Fisheries Queensland will be investigating further in order to inform fishery management options. These include investigation of how fishing mortality varies spatially in the areas that have been fished most heavily. The construction of a new GIS layer for the rotational zoning scheme will enable catch and effort trends to be investigated at the level of individual zones. These investigations will be important to inform spatially-based management options, if relevant.

Information from this assessment and the survey completed earlier this year will also be used to add value to concurrent but separate research projects such as the Reef Integrated Monitoring Evaluation program. This monitoring program will also investigate catch and effort at the level of rotational zones.

4.5 Conclusions

The black teatfish fishery is a commercially valuable stock in Queensland. Currently the assessment estimates that the black teatfish populations in Queensland the biomass ratio in 2021 was 40%–42% of unfished biomass in 1877. The current levels of catch can rebuild the stock to 60%, however the number of years required to achieve this is uncertain. The closure of the fishery between 2000 and 2019 led to a rebuilding of stocks but it was lower than expected. The main features of the assessment in this report are the long time series of catches and the new findings that depensation may have been occurring in areas open to fishing. This information might lay the groundwork for adopting precautionary measures that can be conservative (Woodby et al. 1993), and inform the development of future stock assessments. The main factors that may have contributed to an unrealistically low biomass ratio in 2021 are historical catches being too high (observation uncertainty) and steepness being too low (estimation uncertainty). More years of available data in future (particularly catch rates) may partly overcome estimation uncertainty in the steepness parameter, however it is unclear whether estimates of historical catch can be better resolved in the near term future.

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Appendix A Model base case and alternate scenario

A.1 Description

Two models were developed, each with different levels of historical catch (Figure A.1).

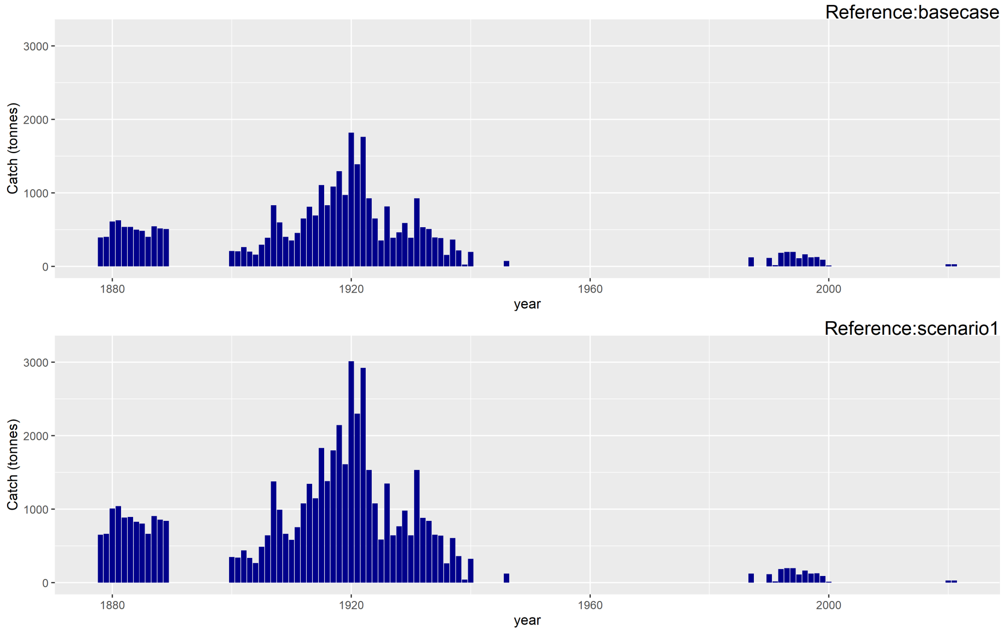

Figure A.1: Historical catch of black teatfish in Queensland for the basecase and alternate scenario

A.2 Model fits

The basecase and alternate scenario models were fitted to biomass estimates from Skewes et al. (2014) (Figure A.2). The models fitted the data reasonably well, except for one outlier in 1995. This value appears to be an estimate to initiate the dynamics in Skewes et al. (2014).

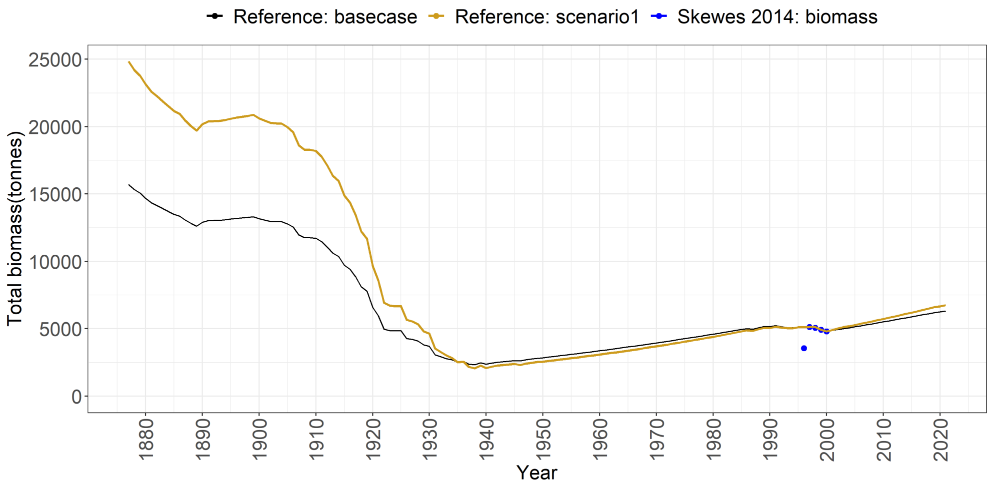

Figure A.2: Estimated biomass from the base case and alternate scenario models fitted to fishery independent survey biomass from Skewes et al. (2014) for black teatfish from 1877 to 2021

A.3 Model outputs

The base case and alternate scenario models resulted in differences in estimates of starting biomass in 1877 and total biomass ratio in 2021 (Figures A.3).

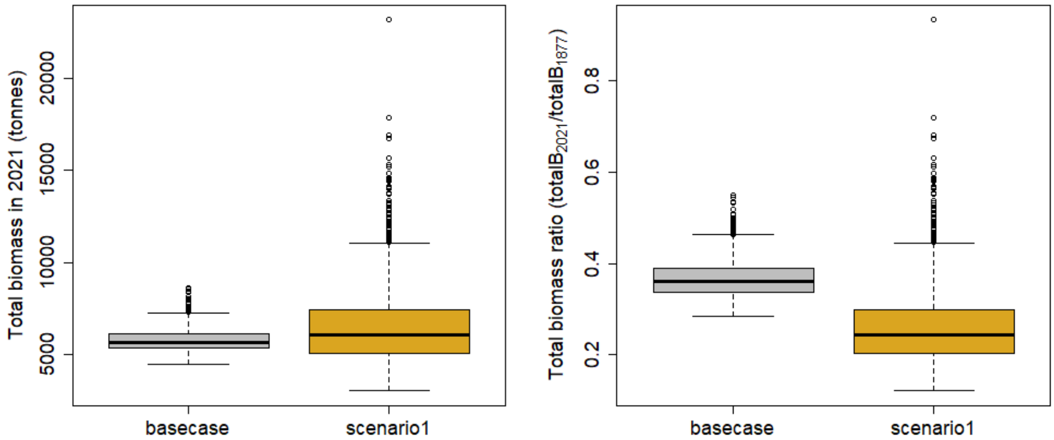

Figure A.3: Evaluation of the base case and alternate scenario total biomass estimate in 2021 and total biomass ratio in 2021 relative the unfished biomass in 1877.