Stock assessment of Ballot's saucer scallops (*Ylistrum balloti*) in Queensland, Australia

2021

Queensland Government

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Summary

The Queensland east coast Ballot's saucer scallop (*Ylistrum balloti*, formerly *Amusium balloti*) is a marine bivalve mollusc with a hinged shell. Saucer scallops can potentially grow to about 12 to 14 cm in shell height and, in some instances, live for up to 4 years. Scallops generally mature between 11 and 18 months of age.

The main fishing ground for saucer scallops is between Yeppoon and Hervey Bay in Queensland waters. Here they form a single population, and trawl fishery management is spatially designated as region 3. Scallops east of K'gari, Fraser Island, are likely to be less connected to the main ground and are managed separately. Assessment results were focused for region 3.

The fishery currently harvests scallops by commercial otter trawling, with a minimum legal shell height of 9 cm. For the 2020 fishing year (1 November 2019 to 31 October 2020), region 3 scallop management was by a total allowable effort quota (effort units), six permanently closed scallop replenishment areas, a no-take scallop closure from 1 May to 30 November (trawling for other species was allowed) and no fishing from 20 September to 1 November.

Before 2002, harvest of legal sized scallops in region 3 were usually greater than 700 tonnes of meat weight per fishing year, and peaked in 1993 at over 1800 tonnes (Figure 1). Since 2011, annual harvests were mostly less than 400 tonnes. Harvest of legal sized scallops in the 2018, 2019 and 2020 fishing years were 162 tonnes, 246 tonnes and 100 tonnes (meat weight) respectively for the management stock in region 3.

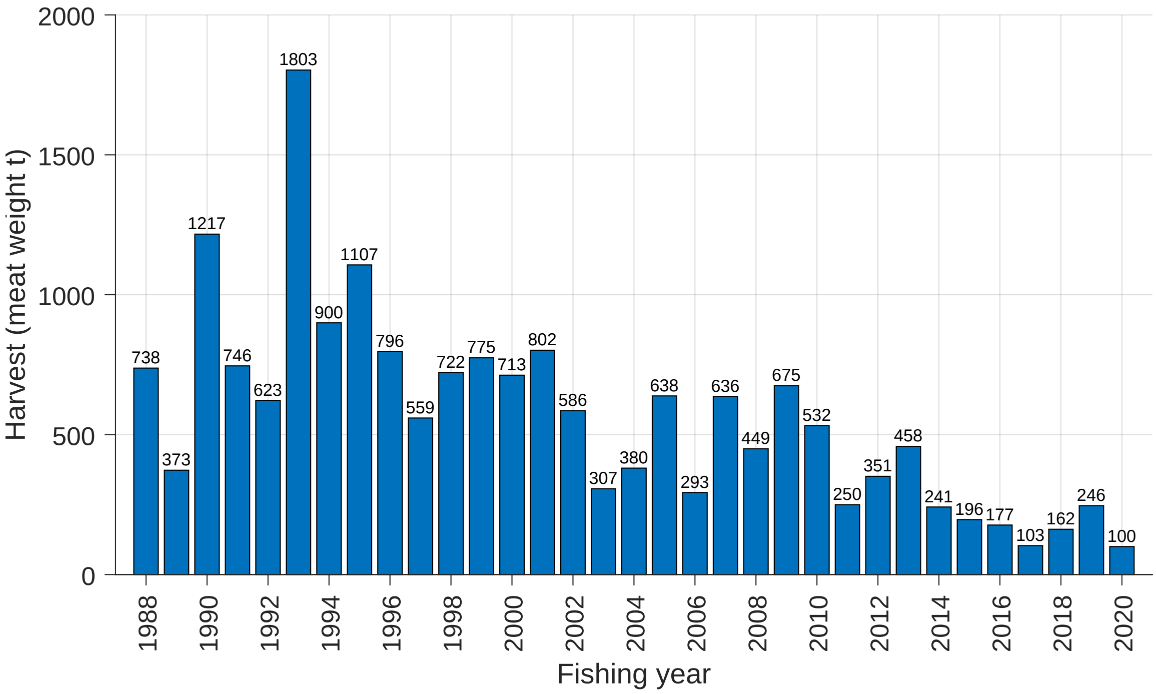

Figure 1: Annual harvests from 1988 to 2020 from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

Abundance measures of standardised catch rates of legal sized scallop for region 3 declined from 9 baskets per boat day in December 2019 to 4 baskets per boat day in April 2020 (Figure 2).

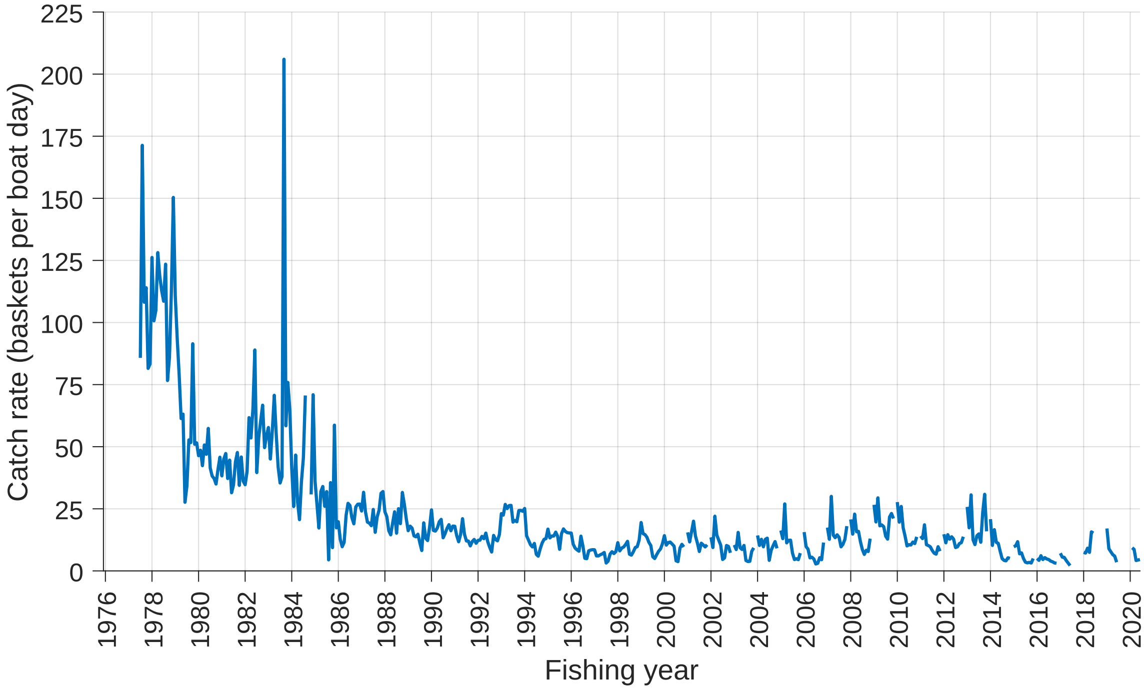

Figure 2: Standardised monthly catch rates from 1977 to 2020 from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

Commercial sized scallop density (number of legal sized scallops per hectare in October) from the fishery independent survey decreased from 38 to 13 scallops per hectare from 2019 to 2020 in region 3 (Figure 3).

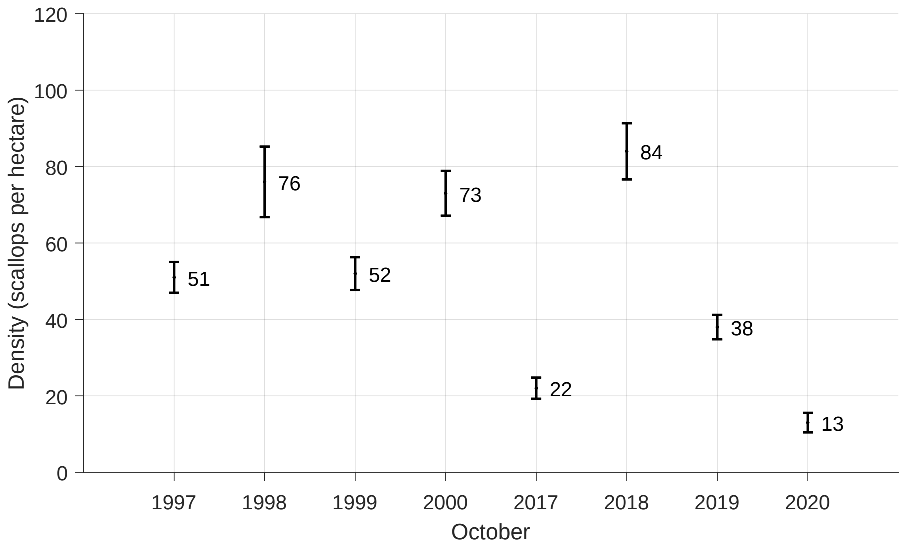

Figure 3: Mean modelled commercial sized scallop densities per hectare from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)–estimates included the scallop replenishment areas

The region 3 stock assessment input data were monthly harvest totals (1956–2020), monthly standardised catch rates (1977–2020), and October survey density (1997–2000 and 2017–2020).

A previous stock assessment for region 3 component of the biological stock was published in 2020. Results suggested the 2019 spawning biomass was at 17% (95% confidence interval 11–24%) of unfished level in 1956.

Results from this assessment suggested that the 2020 spawning biomass in region 3 was at 12% of unfished biomass in 1956 (95% confidence interval 8–18%) (Figure 4). Spawning biomass estimates declined from 2018 to 2020, mainly due to the decline in catch rates and survey scallop density from 2018 to 2020.

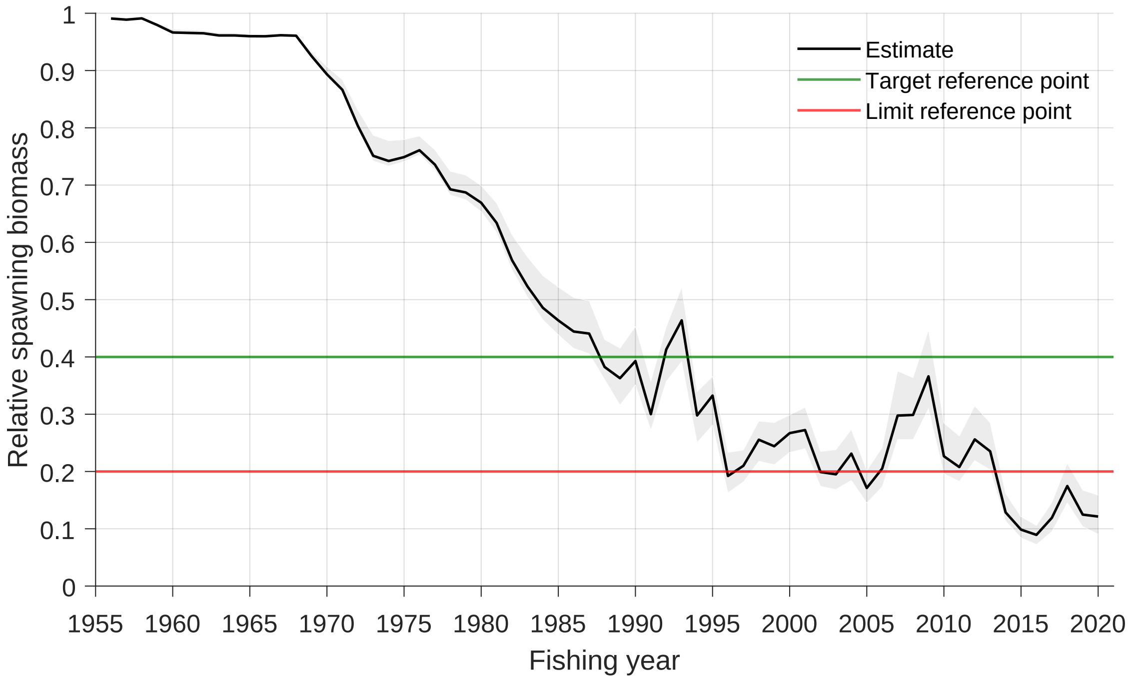

Figure 4: Spawning biomass ratio (±95% CI) from 1956 to 2020 from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

Allocated effort units in the scallop fishery for November 2019 to October 2020 in region 3 were 118 635 effort units (2157 boat-days). Forecasts, following the harvest strategy policy, predicted that zero effort units (no fishing) were required for 13 years to build the spawning biomass to 40% of unfished spawning biomass (relative to levels at 1956) (Table 1). If the spawning biomass rebuilt to 40% of unfished spawning biomass, then the potential yield from the region 3 fishery was estimated to be around 350 tonnes per year. This is in contrast to forecasts estimated under the current effort, which indicated that spawning biomass would not reach 40% of unfished spawning biomass in the next twenty years.

The previous stock assessment cautioned that there were grounds to treat rising sea surface temperature effects carefully. In the southern end of the Great Barrier Reef (where the Queensland scallop fishery is located) sea surface temperatures have warmed, on average by 0.12 °C per decade since 1950. If it is the case that rising sea surface temperature negatively affects scallops, then potential yields from the fishery may be lower than projected. This aspect is important to consider in effort unit settings when developing harvest strategies from results in this assessment report.

Table 1: Current and target indicators for the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

Parameter	Estimate
Current spawning biomass (relative to unfished) 2020	12%
Current harvest (tonnes meat weight) 2020	100 tonnes
Current scallop effort units 2020	118 635 effort units
Harvest proportions	All commercial scallop otter-trawl
Maximum sustainable yield biomass (relative to unfished)	44%
Potential harvest at 40% biomass (relative to unfished)	350 tonnes (321–411 tonnes)
Harvest strategy effort units to build to 40% spawning biomass	0 effort units
Time to build to 40% spawning biomass	13 years

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This report is an update of Wortmann et al. (2020) and hence much of the text is reproduced here.

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Glossary

Term	Definition
B	Exploitable biomass: the combined weight of legal sized scallop
B_{40}	Exploitable biomass equal to 40% of unfished exploitable biomass
B_{MSY}	The exploitable biomass that can support a potential harvest of MSY
Ballot's saucer scallop	*Ylistrum balloti*, formerly *Amusium balloti*, referred to as saucer scallop in this document
BRD	Bycatch reduction device
CSH	Commercial shell height (maximum shell diameter, from any angle)
eu	effort units = standardised boat-days $\times$ standardised hull units
Density	Number of scallops per hectare
Fishing year	The year from November until October the following year-for example, fishing year label 2020 was from November 2019 to October 2020, where November was fishing month 1 and October was fishing month 12
FRDC	Fisheries Research and Development Corporation www.frdc.gov.au
GLM	Generalised linear model
HP	The power of an engine measured in terms of horsepower
Htrawl	Voluntary daily trawl logbook records of prawn and scallop catch rates prior to 1988
M	Natural mortality
LMM	Linear mixed model to standardise catch rates
MCMC	Markov chain Monte Carlo methods
ML	Maximum likelihood
MLS	Minimum legal size – commercial shell measure
MSY	Maximum sustainable yield
-LL	Negative log likelihood
NOAA	The National Oceanic and Atmospheric Administration is an American scientific agency
Region 3	The scallop fishery for the main fishing zones of Yeppoon, Bustard Head and Hervey Bay, and excludes the K'gari zone, Fraser Island
REML	Restricted maximum likelihood, an estimation method in linear mixed models
SH	Shell height (vertical scientific measure)
Spawning biomass	Number of eggs (spawning egg production) used to measure spawning biomass
SRA	Scallop replenishment area
SST	Sea surface temperature
t	Tonnes of scallop meat
TED	Turtle exclusion device

1 Introduction

The Australian east coast Ballot's saucer scallop (*Ylistrum balloti*, formerly *Amusium balloti*) is a marine bivalve mollusc with a hinged shell. They belong to the taxonomic family Pectinidae. Saucer scallop shells are white on the lower side and brown on the upper half shell. They can potentially grow to about 14 cm in shell height and, in some instances, live for up to 4 years (Campbell et al. 2010a; Dredge 1985). In this document, Ballot's saucer scallop is referred to as 'saucer scallop'.

Saucer scallops on the main fishing ground between Yeppoon and Hervey Bay are a single stock (Dredge 2006), with scallops that spawn east of K'gari, Fraser Island, likely to be less connected to the main ground. K'gari is associated with irregular and infrequent scallop catches. Southward ocean currents do not support a linkage from spawning in K'gari to recruitment to the main fishing grounds Hervey Bay and north.

The east coast otter trawl fishery is divided into five management units. The scallop fishery is region 3, south of 22° S to Hervey Bay (Figure 1.1). There are six scallop replenishment areas (SRAs) located off Yeppoon, Bustard Head and Hervey Bay. The SRAs were originally implemented as the *Fisheries (emergency closed waters) Declaration 1997* (Queensland Government 1994). The declaration was put in place due to concerns of overfishing as evidenced by low survey numbers of young scallop (low recruitment). In 1999 industry pushed for a rotational harvest system and this was set up under the *Fisheries (East Coast Trawl) Management Plan 1999* (Queensland Government 1999). The aim was to allow industry to rotationally harvest the larger legal sized shell from ten SRAs while still retaining a certain level of protection to the stock. This was in place from 2001–2003. The opening and closing of ten areas was considered too complicated and the Plan was amended with the SRAs changed to the current format on 31 October 2003. The current format consists of six SRAs with two in each major area. The rotation for these SRAs occured every September and January allowing for an open period of 9 months and a closed period of 15 months each rotation. In January 2017 the SRAs were permanently closed because of low stock levels.

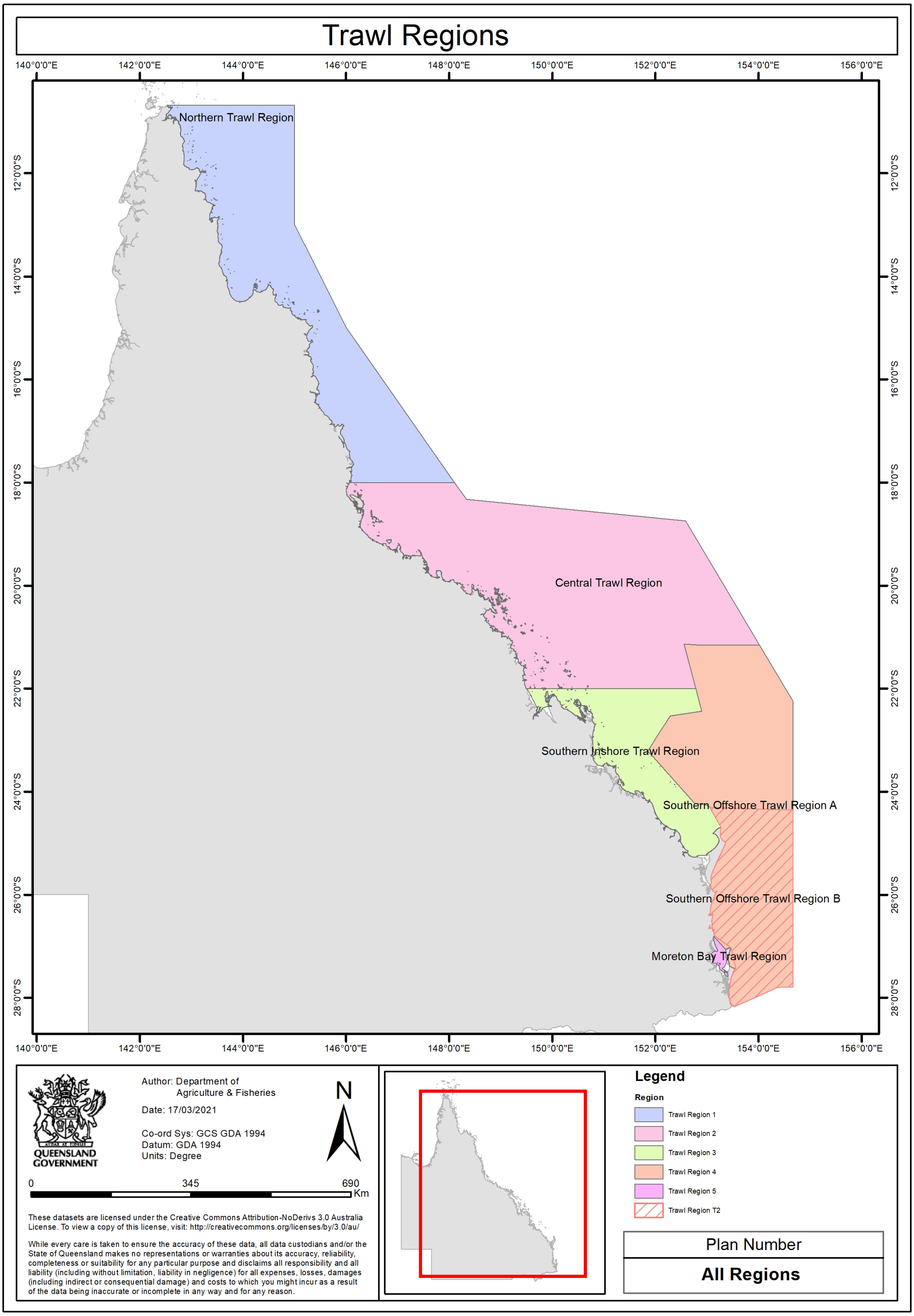

Figure 1.1: East coast trawl fishery divided into five management units (Department of Agriculture and Fisheries 2019)—the saucer scallop fishing sector is the southern inshore trawl region, region 3, south of 22° S to Hervey Bay (shaded green)

Scallop spawning success and survival can vary depending on environmental conditions. Scallops normally spawn during winter and spring, and release eggs and sperm into the water where fertilisation takes place (Dredge 1981). Most scallops with a shell height greater than 9 cm can spawn during the season. By November, spawning is normally complete, and most scallops then allocate energy into growth before spawning again next winter.

Small scallop larvae hatch from the fertilised eggs. After about one day, larvae enter a pelagic phase and spatially disperse with ocean currents. Generally, scallops have a larval phase of up to 30 days. After this time, they settle to the sea floor. Once settled, the juvenile shells, known as 'spat', grow rapidly into juvenile scallop of 5 cm shell height (SH) and appear to create aggregations or beds of scallops. By about 12 months of age, they grow to about 9 cm shell height as adults, mature and spawn.

Otter trawling for scallops in Queensland is generally by vessels 15–20 m length. The vessels typically have main engines of 300–400 horsepower (HP) and tow nets (combined main nets plus try gear) up to 55 m wide at a speed of 2.3–2.6 knots (Yang et al. 2016). The main trawl nets are spread by kilfoil/lourve otter boards with 88 mm square mesh net cod-end for bycatch reduction device (BRD). In 2016–2018, about 100 vessels per year reported scallop harvest, compared to around 300 vessels per year in 1995–1997 (O'Neill et al. 2020).

Management of scallop fishing has varied over time (Table 1.1, O'Neill et al. (2020)). Harvests before 1987 had smaller minimum legal size (MLS) limits (commercial shell height, CSH, of less than 9 cm). From 1987, seasonal minimum legal sizes of 9 cm (CSH) and 9.5 cm (CSH) applied. A number of spatial closures have applied since 1997, including the current permanent closures, although these were fished rotationally from 2001 to 2016.

Table 1.1: Management changes applied to saucer scallop in Queensland waters

Description	Date	Management change
Commerial shell height (CSH)	Pre-November 1980	No minimum legal size (MLS)
	November 1980	8 cm
	July 1984	8.5 cm
	October 1987	9 cm
	March 1989	9.5 cm April–October, 9 cm November–March
	May 1989	9.5 cm May–October, 9 cm November–April
	Post-May 2009	9 cm year-round
Net and mesh sizes	Pre-1984	No restrictions
	July 1984	7.5 cm mesh restriction
	Post-November 1984	8.2 cm mesh restriction, 109 m combined head and foot rope length restriction
	March 2015	8.8 cm square mesh cod-end
Daylight trawl	October 1987–December 1987	Daylight trawl ban
	Post-February 1989	Daylight trawl ban
Effort	November 2019	Annual effort cap of 118 635 eu (2145 boat-days)
	November 2020	Annual effort cap of 80 000 eu (1454 boat-days)
Closures	November 1988	Designated shucking areas
	February 1989	Three 10 × 10 minute closed areas
	May 1989	Closed areas removed
	1997–2000	3 permanently-closed ‘scallop replenishment areas’
	September 2000	Southern closure (south of 22° S) 20th September–30th October annually
	January 2001	Scallop replenishment areas open rotationally to trawling
	January 2017	Scallop replenishment areas closed, and May to October whole-of-scallop-fishery closure
	November 2019	Additional southern closure (south of 22° S) November annually, no fishing 20 September–1 November
	November 2020	No take scallops 1 May–20 November south of 22° S or earlier if effort cap of 80 000 eu reached, no fishing 23 December–3 January

In 2018 and 2019 the Queensland Department of Agriculture and Fisheries and the University of Queensland conducted work to improve stock model predictions to estimate the current population size of saucer scallops and develop management procedures. The results from the simpler non-spatial model, excluding environmental effects, suggested the 2018 region 3 (Figure 3, page 3) spawning biomass was at 22% (95% confidence interval 17–32%) of the virgin (unfished) level in 1956 (O’Neill et al. 2020). For regular assessments, O’Neill et al. (2020) recommended the nonspatial model for region 3 for ease and consistency, and this was applied in the 2020 stock assessment (Wortmann et al. 2020). The stock assessment in 2020 indicated that spawning biomass was at 17% (95% confidence interval 11–24%) of the virgin (unfished) level in 1956 (Wortmann et al. 2020). This stock assessment used the nonspatial model for region 3 from O’Neill et al. (2020) and Wortmann et al. (2020) with updated data to include the 2020 fishing year. Estimates are provided to support implementation of the *Queensland sustainable fisheries strategy 2017–2027* (Queensland Government 2020). Forward projections for levels of fishing effort are calculated.

2 Methods

Fishing year was defined as the year from November until October the following year. For example, fishing year label 2020 was from November 2019 to October 2020, where November was fishing month 1 and October was fishing month 12.

Unfished spawning biomass was defined as the spawning biomass pre-1956.

2.1 Data sources

Data sources included in this assessment are detailed in Table 2.1 and are described in more detail in the following sections. New data in this stock assessment compared to the previous stock assessment (Wortmann et al. 2020) were:

- Commercial harvest data for the 2020 fishing year
- Standardised catch rates up to and including the 2020 fishing year
- The inclusion of the October 2020 survey density data (number of scallops per hectare) for age group 0+ and 1+ from FRDC project 2017-048 (Courtney et al. 2020).

Table 2.1: Data inputs for the population model

<table>
<tr><th>Data</th><th>Years</th><th>Source</th></tr>
<tr><td rowspan="3">Commercial</td><td>1956–1987</td><td>Total annual meat weight harvest (Dredge 2006)</td></tr>
<tr><td>1977–1987</td><td>Voluntary Htrawl catch rate data</td></tr>
<tr><td>1988–2020</td><td>Compulsory CFISH logbook data collected by Fisheries Queensland</td></tr>
<tr><td>Fishery independent survey</td><td>October 1997–2000, 2017–2020</td><td>Agri-Science Queensland survey data FRDC project 2017-048 (Courtney et al. 2020)</td></tr>
</table>

2.2 Harvest

Historical commercial catch data 1956–1987 was from Dredge (2006), and is described in section 3.1 of O'Neill et al. (2020)

Commercial catch data 1988–2020 was from CFISH logbooks. In the data extraction from CFISH logbooks for the previous stock assessment (up to October 2019, Appendix 6.1 in Wortmann et al. (2020)), there were catch records from the closed months of scallop fishing. These catch records were present in the current data extraction, as well as 60 baskets recorded in November 2019 which was closed to scallop fishing. As in Wortmann et al. (2020), any scallop catch recorded during a closure time was included in the harvest data. The CFISH logbooks recorded the number of baskets, and a conversion from number of baskets to meat weight was done using the formula in Table 2.2. The formula is a monthly formula, with baskets in January–March having a higher meat weight.

2.3 Density data

A fishery independent trawl survey estimated scallop densities (number of scallops per hectare) for 2020 (Courtney et al. 2020). The survey focused on scallops grouped by age (0+ or 1+, depending on their size) in October of 2020. Aged densities 0+ were for shell heights (SH) $<$ 7.8 cm, and aged densities for $\geq$ 1+ were for shell heights $\geq$ 7.8 cm. The spatial abundance of the two age groups supplied provided insight on scallop recruitment of small shell, and on mortality rates of large scallop.

The stock assessments in O'Neill et al. (2020) and Wortmann et al. (2020) used mean scallop densities from each October survey. They were estimated using local kriging (geo-statistical interpolation) models on the survey data (O'Neill et al. 2020). This assessment used new methods from Courtney et al. (2020) to derive mean scallop densities using a Quasi-Poisson generalised linear model (GLM) with the predictive variables year, strata, lunar phase, time-of-night and turtle exclusion device (TED) or bycatch reduction device (BRD) (representing nets without devices, nets with only TEDs, nets with only BRDs, and nets with both devices). A detailed description of these methods may be found in Appendix 16 in Courtney et al. (2020). The adjusted means provided a more robust and reliable index of abundance for detecting change and trends in the scallop population size. The adjusted means were similar to the means from local kriging in O'Neill et al. (2020) and Wortmann et al. (2020). Predictions were derived for three groups:

- 0+ age group for scallop sizes $<$ 7.8 cm SH
- 1+ age group for scallop sizes $\geq$ 7.8 cm SH
- Commercial legal sized scallops $\geq$ 8.8 cm SH. The 8.8 cm SH was equivalent to 9 cm in commercial measurement (CSH).

The predictions were for the saucer scallop fishing grounds between Yeppoon and Hervey Bay, including scallop replenishment areas, in the month of October for the years 1997–2000 and 2017–2020. Surveys in the years 2001–2006 were from scallop replenishment areas only and were excluded from the input data for the stock assessment.

The densities were scaled up by a trawl efficiency factor of 0.3 (Wortmann et al. 2020).

2.4 Abundance indices

2.4.1 Commercial catch rates

The datasets and methods for the catch rate standardisations were collated and developed from the projects Yang et al. (2016), O'Neill et al. (2020) and Wortmann et al. (2020). The catch rate standardisations used the statistical application of linear mixed models (LMM) using restricted maximum likelihood (REML). The analyses used daily logbook information per vessel operation. The catch rate standardisation was programmed in Genstat (VSN International 2021).

As in previous projects, catch rates were standardised for changes in fishing power through time to account for shifts in the fleet's vessel-profile (e.g. changing number of higher versus lower catching vessels) and variation in gear technologies (e.g. engine sizes, net types, and the use of global positioning systems). Trends in vessel gears from 1988–2020 and changes in fishing power from gear changes, technology upgrades and hours fished from 1988–2020 are shown in Appendix A.

The catch rate standardisation followed analysis 3 and 4 in section 3.1 of O'Neill et al. (2020). The two analyses evaluated catch rates for 1988–2020 and 1977–2020. The 1977–2020 analysis used fishing power parameter estimates from the first 1988–2020 analysis. The catch rate data for 1977–1987 came from voluntary daily trawl logbook records by 30×30 minute grids. The data collections were from research projects prior to 1988, and known as the historical catch rate data or Htrawl. This dataset was based on 5–30% per year of fishers voluntary participation in the logbook program (O'Neill et al. 2005; Yang et al. 2016). Section 8.2.1.2 of Yang et al. (2016) gives a description of the Htrawl data.

Catch rates were standardised for 1988–2020 (analysis 3 from O'Neill et al. (2020)) using:

$$\text{Log(baskets per boat day)} \sim \begin{array}{l}\text{fishingyear*fishingmonth*area + log(hours per boat day) + log(hp) +}\\ \text{log(speed) + sonar + gps + nettype + ggear + random(boat label code) +}\\ \text{random(grid)}\end{array} \qquad (2.1)$$

where

- area = Yeppoon, Bustard Head, Hervey Bay
- hours = hours fished
- hp = engine horsepower
- ggear = ground gear (drop chain, looped ground chain, drop rope with chain or other less used types)
- nettype = net type (twin, triple, quad or five gear).

The catch rates for 1988–2020 were standardised to a modern-day boat. The standardisation factors were:

- Use of GPS and sonar
- Net type of quad gear (Figure A.3)
- Ground gear of drop chain (Figure A.2)
- Hours fished equal to the average of log hours fished for 2007–2020 (12 hours) (Figure A.5)
- Engine power equal to the average 2020 engine power of 343 HP (Figure A.1)
- Boat that matched the maximum annual average boat effect-for this catch rate analysis, this was in 2007 (Figure A.6).

Catch rates were standardized for 1977–2020 using analysis 4 of O'Neill et al. (2020):

$$\text{Offsetlog} = \begin{array}{l}\text{log(hp)*0.3792 + sonar*0.1513 + gps*0.03639 +}\\ \text{(nettype.eq.3)*0.3816 + (nettype.eq.4)*0.3319 + (nettype.eq.5)*0.2432 +}\\ \text{(ggear.eq.3)*0.03875 + (ggear.eq.4)*-0.08845 + (ggear.eq.5)*-0.19545}\end{array} \qquad (2.2)$$

$$\text{lognoffset} = \text{log(baskets)} - \text{offsetlog} \qquad (2.3)$$

$$\text{lognoffset} \sim \text{fishyear*fishingmonth + log(hours per boat day) + random(boat label code) + random(grid)} \qquad (2.4)$$

where

- The coefficients were estimated from the 1988–2020 catch rate standardisation model, a high positive coefficient means many scallops would be caught
- ggear.eq.3 is looped ground chain
- ggear.eq.4 is drop rope with chain
- ggear.eq.5 is other less used types
- nettype.eq.3 is triple gear
- nettype.eq.4 is quad gear
- nettype.eq.4 is five gear.

Catch rates for 1977–2020 were standardised to the same modern boats setting as above. Fishing year by month trend for January 1977 to October 2020 for region 3 was calculated. The result focused on a single fishing year × month catch rate index for region 3.

2.5 Natural mortality

The updated estimate of natural mortality M with no seasonal variation from the previous stock assessment (Wortmann et al. 2020) was used for this assessment. The updated value of natural mortality came from tag recapture experiments in Courtney et al. (2020). The annual mean estimate of M for the whole fishery is 1.461 per year or 0.1217 per month (Courtney et al. 2020).

2.6 Population model

The nonspatial model for region 3 in O'Neill et al. (2020) and Wortmann et al. (2020) was used for this stock assessment. This model described the scallops as a single stock in region 3 where no environmental effects were included. The model was an age-based population dynamic model that assessed scallops monthly from the fishing years 1956 to 2020, counting scallop age classes from one to 48 months (4-year life cycle), with a Beverton-Holt stock-recruitment relationship. The model accounted for the processes of scallop births, growth, reproduction and mortality in every fishing year-month. The model was written in MATLAB version 2020a (Mathworks 2020).

Number of scallops N_{ta}:

The number of scallops N_{ta} at age a at monthly time-step t was modelled with the following recursive equation,

$$N_{ta} = \begin{cases} R_t & \text{for } a = 1 \\ N_{t-1,a-1} \exp(-Z_{t-1,a-1}) & \text{for } a = 2, \ldots, 48 \end{cases} \tag{2.5}$$

Note that N_{ta} represented the number of scallops at the beginning of time-step t; in addition, it also represented the number of scallops at the end of time-step $t - 1$.

Recruitment number R_t:

The number of scallops recruited R_t at age group $a = 1$ at time-step t was defined as follows,

$$R_t = \frac{E_{y-1}}{(\alpha_k + \beta_k E_{y-1})} \exp(\eta_y)\phi_t, \tag{2.6}$$

where η_y was annual recruitment deviation of fishing year y and $\eta_y = 0$ for $y = 1956, \ldots, 1987$.

Annual number of eggs E_y:

The number of eggs E_y produced in fishing year y was defined by,

$$E_y = 0.5 \sum_t \sum_a N_{ta} \times \text{Mat}_a \times \text{Fec}_a \times \text{Spawn}_t \tag{2.7}$$

- Mat_a was the proportion of scallop mature at age a.
- Fec_a was the number of eggs produced by a scallop at age a.
- Spawn_t was the 12 month spawning pattern, defining proportion of annual egg production produced at time-step t. It was important to note that the sum of Spawn_t over the 12 fishing months of fishing year y was equal to 1.
- The value 0.5 represented the assumption that half of N_{ta} were females.

Recruitment pattern ϕ_t:

For each fishing month t, within each fishing year, the proportion of recruitment was modelled as follows,

$$\phi_t = \exp\left(\kappa \cos\left(2\pi(m_t - \theta)/12\right)\right) / \sum_{m_{t'}=1}^{12} \exp\left(\kappa \cos\left(2\pi(m_{t'} - \theta)\right)\right) \tag{2.8}$$

where m_t was the fishing month at time-step t in fishing year y and ranged from 1 (November) to 12 (October). For each fishing year, the sum over 12 months was equal to $\sum_t \phi_t = 1$. Notice that Equation 2.8 is a modification version of the von Mises distribution for discrete variables, and circumvents the use of the modified Bessel function of order 0 to reduce computation cost.

Survival rate $\exp(-Z_{ta})$:

Survival rate $\exp(-Z_{ta})$ at age a at monthly time-step t was the product of the survival rates from natural mortality M and harvest rates u_t. The mathematical expression was written with the following form:

$$\exp(-Z_{ta}) = \exp(-M)(1 - v_{ta} u_t) \tag{2.9}$$

The equation factors represented survival rates from natural mortality and fishing, respectively.

Harvest rate u_t:

$$u_t = C_t / (B_t^{(1)} b_t^{-1}), \tag{2.10}$$

where C_t represented the total harvest (in baskets) at time-step t, and b_t was the converter for basket and meat weight.

Midmonth exploitable biomasses—forms $B_t^{(1)}$ and $B_t^{(2)}$:

$$B_t^{(1)} = \sum_a N_{ta} w_a v_{ta}^* \exp(-0.5M), \tag{2.11}$$

$$B_t^{(2)} = \sum_a N_{ta} w_a v_{ta}^* \exp(-0.5M) \sqrt{1 - u_t} \tag{2.12}$$

$B_t^{(1)}$ and $B_t^{(2)}$ were presented in kilograms. The difference between the two was that $B_t^{(1)}$ expressed the midmonth exploitable biomass before fishing and $B_t^{(2)}$ the exploitable biomass in the middle of a fishing pulse. $B_t^{(1)}$ was used to calculate harvest rates and should be larger than C_t. $B_t^{(2)}$ was used to connect catch rates. Use of equation $B_t^{(1)}$ with fixed last year values of v_{ta}^*, described biomass trends without MLS changes.

Vulnerability to fishing—v_{ta} and v^*_{ta}:

Vulnerabilities v_{ta} and v^*_{ta} of age a at time-step t incorporated the probability density of length $f_a(\ell)$ at age a, selectivity of nets $v_t(\ell)$, and selectivity of tumbler $G_t(\ell, \text{MLS}_t)$ with respect to minimum legal size MLS$_t$. v_{ta} also included discard mortality d_t. v^*_{ta} was used to formulate midmonth exploitable biomasses (Equations 2.11 and 2.12) and v_{ta} was used for survival rate of Equation 2.9.

$$v_{ta} = \int_\ell f_a(\ell)v_t(\ell)(G_t(\ell, \text{MLS}_t) + (1 - G_t(\ell, \text{MLS}_t))d_t)d\ell, \tag{2.13}$$

$$v^*_{ta} = \int_\ell f_a(\ell)v_t(\ell)G_t(\ell, \text{MLS}_t d\ell. \tag{2.14}$$

Specifically, for the period prior to 1981, there was no minimum legal size, and $v_{ta} = v^*_{ta}$, that is,

$$v_{ta} = v^*_{ta} = \int_\ell f_a(\ell)v_t(\ell)d\ell. \tag{2.15}$$

Fishery data indicators—midmonth catch rates $c_t^{(f)}$, density for 0+ $c_t^{(s_{0+})}$ and 1+ $c_t^{(s_{1+})}$:

$$c_t^{(f)} = q_t B_t^{(2)} b_t^{(-1)}, \tag{2.16}$$

$$c_t^{(s_{0+})} = \frac{q^{(s_{0+})}(\sum_{a=1}^{48} N_{ta} \exp(-0.5M) P_a(\ell < 78mm))}{A}, \tag{2.17}$$

$$c_t^{(s_{1+})} = \frac{q^{(s_{1+})}(\sum_{a=1}^{48} N_{ta} \exp(-0.5M) P_a(\ell \geq 78mm))}{A} \tag{2.18}$$

where q_t was the catchability at time-step t, $q^{(s_{0+})}$ and $q^{(s_{1+})}$ were the catch efficiency for 0+ and 1+ scallop, respectively, and A was the area of region 3. The units of $c_t^{(f)}$ was baskets per standardised boat-day, and $c_t^{(s_{0+})}$ and $c_t^{(s_{1+})}$ were numbers per hectare. Catchability q_t was modelled to reflect the closure effect (see model parameters). We note that $q^{(s_{1+})}$ was a fixed setting at 0.3 (Wortmann et al. 2020).

Fishery log standardised catch rates or log survey densities:

$$l = \frac{n}{2}(\log(2\pi) + 2\log(\sigma) + (\hat{\sigma}/\sigma)^2), \tag{2.19}$$

where $\sigma = \max(\hat{\sigma}, \sigma_{\min})$, $\sigma_{\min}$ was the standard error from the LMM (REML) log predictions $\hat{c}$ of catch rates c or densities, $\hat{\sigma} = \sqrt{\sum(\log(c) - \log(\hat{c}))^2/n - 1}$, and n was the number of monthly data.

h steepness:

$$l_h = \begin{cases} 0.5(\frac{\xi - \log(19)}{1.2})^2 & \text{, if } \xi > \log(19) \\ 0.5(\frac{\xi - \log(19)}{1.2*0.3333})^2 & \text{, if } \xi < 0 \end{cases} \tag{2.20}$$

(O'Neill et al. 2018)

θ:

$$l_\theta = 0.5(\frac{\theta - 5}{0.5})^2, \text{ if } \theta > 15 \text{ or } \theta < 0 \tag{2.21}$$

κ:

$$l_\kappa = 0.5(\frac{\kappa - 20}{0.5})^2, \text{ if } \kappa > 20 \tag{2.22}$$

harvest rate u:

$$l_u = 0.5 \sum (\frac{\log(C_t + 0.1) - \log(\frac{B_t^{(1)}}{b_t} * 0.8)}{0.005})^2, \text{ if } u \geq 0.8 \tag{2.23}$$

Log recruitment deviations η_y for $y = 1988, ..., 2020$:

$$nssRec = 2020 - 1988$$

$$sigmaRhat = \sqrt{\frac{\sum(\eta_y)^2}{nssRec}}$$

$$sigmaR = \min(\max(sigmaRhat, 01), 0.2)$$

$$l_r = \frac{nssRec}{2}(\log(2\pi) + 2\log(sigmaR) + (\frac{sigmaRhat}{sigmaR})^2)$$

Recruitment parameters to ensure log deviations sum to zero with standard deviation. $\eta = \xi e$, where $e =$ zeros(nparRresid, nparRresid+1);

for i = 1:nparRresid

hh = sqrt(0.5 * i ./ (i + 1));

e(i, 1:i) = -hh ./ i;

e(i, i + 1) = hh;

end; e= e ./ hh;

ξ were the estimated parameters known as barycentric or simplex coordinates, distributed $NID(0, \theta)$ with number nparRresid = number of recruitment years – 1 (Möbius 1827; Sklyarenko n.d.). e was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill et al. 2011).

2.6.1 Model assumptions

Notations to represent time and scallop age were:

- Fishing year y started from 1956 and finished in 2020. Fishing year y was defined as a time interval starting from November of calendar year $y - 1$ to October of calendar year y.
- Population dynamics were presented in monthly time steps t from 1 to 780 (i.e. 12 months × 65 fishing years.)
- Scallop ages were stratified into 48 months denoted by a=1,...,48. Saucer scallops were assumed to live for up to four years of age.

2.6.2 Model parameters

Parameters used in the model are listed in Table 2.2. Attempts were made to estimate as many of the parameters as possible and not fix them outside the model.

Table 2.2: Population model parameters and definitions

	Equations and values	Notes
Known		
ℓ_a	$\ell_a = 104.587(1 - \exp(-0.159a))$	Shell height (length mm) at age a. The estimate of standard deviation of the error term was 2.285 mm (Campbell et al. 2010a).
$f_a(\ell)$	The normal probability density of length at age a, with mean ℓ_a and variance 2.2852.	
$P_a(\ell \leq L)$	$\int_0^L f_a(\ell)d\ell$	The probability of length less than or equal to L at age a.
Mat_ℓ	$\text{Mat}_\ell = \frac{\exp(-8.72+0.1085\ell)}{1+\exp(-8.72+0.1085\ell)}$	Proportion mature at length l, estimated on Dredge (1981) data. For the data, the maturity asymptote was less than one.
Mat_a	$E_a(\text{Mat}_\ell) = \int f_a(\ell)\text{Mat}_\ell d\ell$	Proportion mature at age a, based on Mat_ℓ and $\ell_a \sim N(\ell_a, 2.285^2)$.
Fec_a	$\zeta_a = 3220.708\ell_a^{1.354}$	Fecundity of shell height at age a (Dredge 1981; O'Neill et al. 2005), used in Equation 2.7 to produce annual number of eggs.
Spawn_t	0.0072, t ∈ November 0.0000, t ∈ December 0.0144, t ∈ January 0.0288, t ∈ February 0.0899, t ∈ March 0.1331, t ∈ April 0.1403, t ∈ May 0.1439, t ∈ June 0.1439, t ∈ July 0.1403, t ∈ August 0.0863, t ∈ September 0.0719, t ∈ October	Monthly spawning pattern (Dredge 1981; O'Neill et al. 2005), used in Equation 2.7 to produce annual number of eggs.
w_a	$w_a = 1.259 \times 10^{-9}\ell_a^{3.485}$	Meat weight (kg) at age a (O'Neill et al. 2005), used in Equation 2.11 and 2.12.

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Table 2.2 – *Continued from previous page*

	Equations and values	**Notes**
b_t	6.5, t ∈ November 7, t ∈ December 7, t ∈ January 7.5, t ∈ February 7, t ∈ March 6.5, t ∈ April 6, t ∈ May 5, t ∈ June 5, t ∈ July 5, t ∈ August 5.5, t ∈ September 6, t ∈ October	Baskets to meat-weight conversion (kg per basket) (O'Sullivan et al. 2005), used in Equation 2.10 and 2.16.
$v_t(\ell)$	Logistic retention curves $v_t(\ell) = \frac{\exp(a_t + b_t \ell)}{1+\exp(a_t + b_t \ell)}$ Prior to November 2015, $a_t = -11.287$ and $b_t = 0.2412$. These values represented 88 mm diamond mesh with a Turtle Excluder Device (TED) After November 2015, $a_t = -7.9716$ and $b_t = 0.1136$, for 100 mm mesh with TED and a square-mesh cod-end.	See Figure 9-4 in Campbell et al. (2010a) for 88 mm diamond mesh and TED (in brown colour) and 100 mm mesh with TED and a square-mesh cod-end (in blue colour). In effect, Courtney et al. (2008) figures 1 and 3 suggested selectivity had not changed

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Table 2.2 – *Continued from previous page*

	Equations and values	Notes
$G(\ell, \mathrm{MLS}_t)$	List of MLS_t imposed: • No MLS prior to November 1980. • 80 mm: November 1980 to October 1984. • 85 mm: November 1984 to October 1987. • 90 mm: – November to April in the period of November 1987 to December 1999. – January to April in the period of January 2000 to October 2004. – November to April in the period of November 2004 to October 2009. – November 2009 to October 2018. • 95 mm: • May to October in the period of November 1987 to December 1999. • May to December in the period of January 2000 to October 2004. • May to October in the period of November 2004 to October 2009.	Probability of retention by a tumbler (Campbell et al. 2010a). Tumbler use was sporadic in the 1970s, but was utilised from late 1980.
d	3.3%	Discard mortality (Campbell et al. 2010a).
A	1 256 473.72 (Region 3)	Area from monthly TrackMapper effort maps for January 2000 to April 2018, where fishing effort > 1 hour. Measured in hectares.
Unknown		
R_0 and h	$\alpha_k = E_0(1-h)/(4hR_0)$, $\beta_k = (5h-1)/(4h)$, $R_{0,k} = \exp(\gamma) \times 10^9$, $h = \frac{1+\exp(\xi)}{5+\exp(\xi)}$.	R_0 was recruitment in virgin years prior to fishing. E_0 was the equilibrium total egg production in virgin years, from Equation (3). h was steepness defined as a fraction of R_0 at 20% of the egg production of the population in virgin years. h is in the interval [0.2, 1].
κ and θ		θ and κ were parameters of centre location and concentration of Equation 2.8.

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Table 2.2 – *Continued from previous page*

	Equations and values	Notes
$\exp(-M)$	The survival rate of monthly natural mortality M	Monthly natural mortality is equal to 0.1217 according to the tagging study of Courtney et al. (2020).
q_t	Scallop catchability composed of three components with the form: $\exp(\gamma_q + \gamma_{jan}\delta_t + \gamma_s \cos(\frac{2\pi t}{12})) \times 10^{-7}$, where; δ_t was the indicator function of t with value 1 when time-step t was at the month of closure open (i.e. January fishing month 3) of fishing years 2002–2016; γ_{jan} was the associated coefficient; γ_s was the seasonal effect of the 12-month cycle at phase equal to November (i.e. fishing month 1).	Catchability at time-step t. Note that the seasonal effect γ_s was set to zero in the current analysis.
$q^{(s_{0+})}$	$q^{(s_{0+})} = \exp(\gamma_{q^{(s_{0+})}})$	Catchability of 0+ scallop.

2.6.3 Model uncertainty

The model estimation process in MATLAB consisted of a maximum likelihood (ML) step followed by Markov chain Monte Carlo sampling (MCMC). The maximum likelihood step used MATLAB global optimisation, followed by a customised simulated annealing program to find and check the parameter solutions and estimate the parameter covariance matrix. The maximum likelihood step was effective for identifying optimal estimates for the negative log-likelihood (combined -LL fitting functions). The simulated annealing started from a -LL scaling factor of 100 and then reduced to 10, 1, 0.1 and finally 0.01. For each scaling factor, the annealing process ran for 10 thousand iterations of each parameter. The covariance matrix was built from the differences in the negative log-likelihood with each parameter jump. A customised Markov chain Monte Carlo sampling (MCMC) followed on from the simulated annealing using a -LL scaling factor of one with fixed covariance. The MCMC used parameter-by-parameter jumping following the Metropolis-Hastings algorithm (Metropolis et al. 1953; Hastings 1970)). The final parameter distributions were for 200 000 posterior MCMC samples thinned from one solution stored per 100 samples. MCMC parameter traces were reviewed.

All three fitting procedures (MATLAB optimisation, custom simulated annealing, and custom MCMC) confirmed model convergence and parameter estimates. The three procedures ensured checking and consistency in model fitting.

The model estimated an indicator of scallop spawning biomass abundance for region 3 and reference points and projections for management procedures to support the *Queensland sustainable fisheries strategy 1917–2027*.

Reference points were calculated to a standardised boat-day according to a modern day vessel, defined by a boat with 344 HP, fishing 12 hours a night, with sonar, GPS, quad gear and drop chain, and equal to the maximum average fleet profile. Overall, the boat settings equated to around 55 standardised hull units (effort units = standardised days × standardised hull units (O'Neill et al. 2006)). Reference point estimates assumed the 2020 pattern of monthly fishing. The estimates for the equilibrium reference points were medians from MCMC, with 95% confidence intervals calculated.

2.6.4 Forward projections

Forward projections were undertaken to provide a timeframe based on rebuilding to 40% spawning biomass under a series of available harvest (and effort) scenarios. Forward projections for twenty years were estimated based on the assumption that the fishing effort pattern followed the monthly pattern of the 2020 fishing year (closed May–November), and recruitment was deterministic. The projections were done for levels of fishing effort from no fishing to fishing effort higher than the current allocated effort of 118 635 effort units (Table 2.3):

Table 2.3: Levels of fishing effort for the forward projections

Level of fishing effort	Fishing effort (eu)
No fishing	0 eu
68% of current	80 000 eu
Current	118 635 eu
230% of current	275 000 eu

3 Results

3.1 Model inputs

3.1.1 Harvest estimates

Before 2002, annual harvests were normally greater than 700 t of meat weight per fishing year, and peaked in 1993 at over 1800 t (Figure 3.1). Since 2011, annual harvests were mostly less than 400 t. Harvest of legal sized scallops in the 2018, 2019 and 2020 fishing years were 162 tonnes, 246 tonnes and 100 tonnes (meat weight) respectively for the management stock in region 3. Harvest in the 2020 fishing year was at the lowest it has been historically.

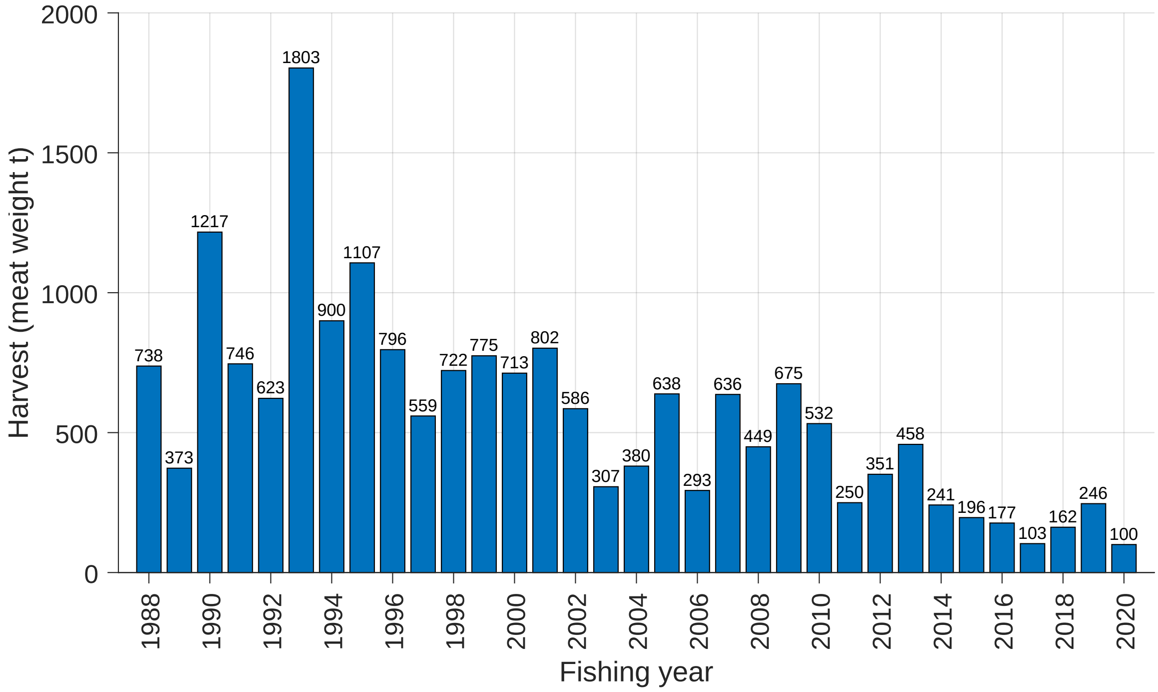

Figure 3.1: Annual harvests from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

Figure 3.2 shows the typical seasonal change in scallop harvest, with scallop harvests by month for the period 1956–2020. Since 2002, clear spikes in harvest occurred in the months of November–January. In the 2020 fishing year, 84% of the scallop harvest was taken in the months from December 2019 to January 2020 (the fishery was closed in November 2019).

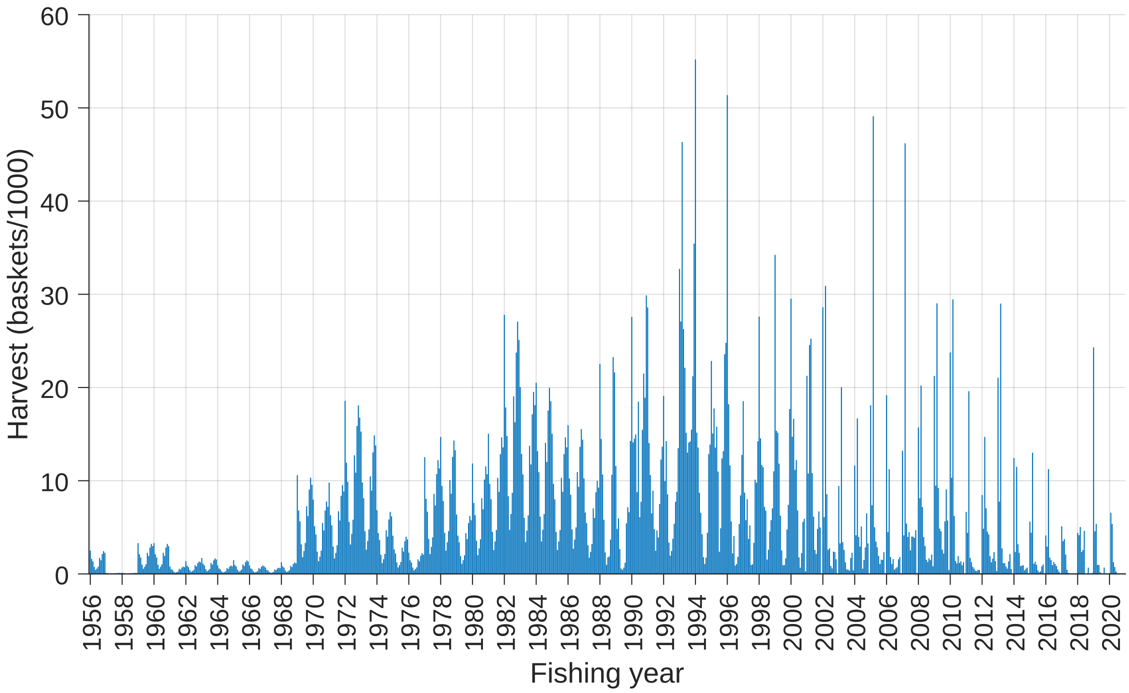

Figure 3.2: Monthly harvests from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

3.1.2 Standardised catch rates

Catch rates declined in the 2020 fishing year, from 9 baskets per boat day in December 2019, to 4 baskets per boat day in April 2020 (Figure 3.3). The 95% confidence intervals on catch rates were generally in the range of ±14–21 baskets per boat day pre-1988, and ±3 baskets per boat day thereafter. The highest catch rate in the 2019 fishing year was in November 2018, at 18 baskets per boat day.

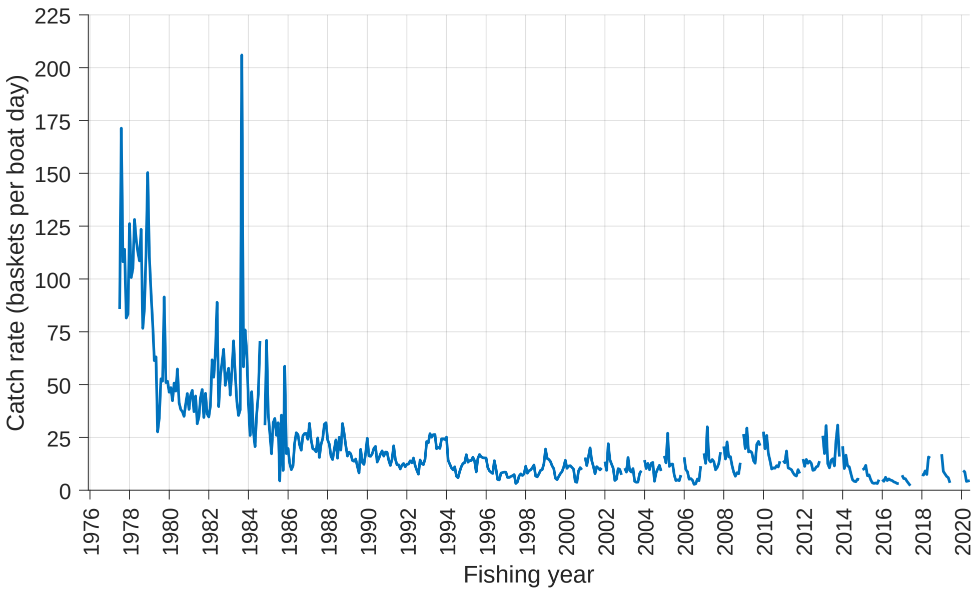

Figure 3.3: Standardised monthly catch rates 1977–2020 from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

Standardised catch rates were lower than the reported-observed catch rate (calculated as the total annual catch divided by total annual effort) (Figure 3.4) due to the following factors:

- Area: Fishers move around to target areas with higher density of scallops, especially in the later years with more technical knowledge. Thus when catch rates were standardised to fishing all grids more equally, then catch rates were lower in the later years—indicating fishing was spatially aggregated (clustered) on scallop patches.
- Hours fished: When catch rates were standardised according to the average hours fished 2007–2020, catch rates were lower in the later years. This was because in the earlier years the median of hours fished was one hour less fishing for scallops (Figure A.5).
- Gear: When catch rates were standardised according to modern gear settings, they were lower in the later years. This is because these technologies and gears were not available in the earlier years and are associated with higher catches (Figure A.1-Figure A.4).
- Boat: When catch rates were standardised according to a modern fleet profile the catch rates in the later years were lower than in the earlier years. In 2020 the boat effect increased slightly indicating that some less efficient boats left the fishery (Figure A.6).

Catch rate diagnostics are given in Appendix B.1.

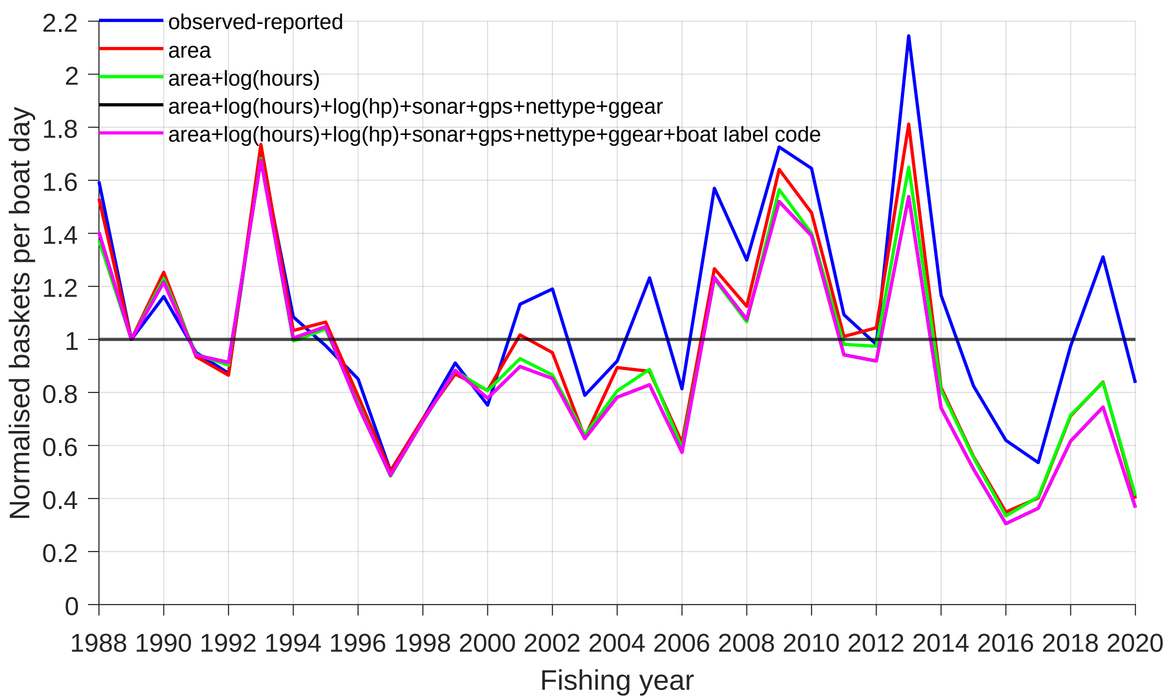

Figure 3.4: Relative influence of each factor in the annual commercial catch rate for 1988–2020 from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

3.1.3 Survey estimates

Scallop density (number of scallops per hectare) from the October survey decreased from 2019 to 2020 for age 0+, age 1+ and legal sized groups (Figure 3.5). For age group 0+ the estimated density in 2020 was 8.97 scallops per hectare (down from 11.5 in 2019), for age group 1+ the estimated 2020 density was 18.5 scallops per hectare (down from 47 in 2019) and for legal sized group the estimated 2020 density was 13 scallops per hectare (down from 38 in 2019).

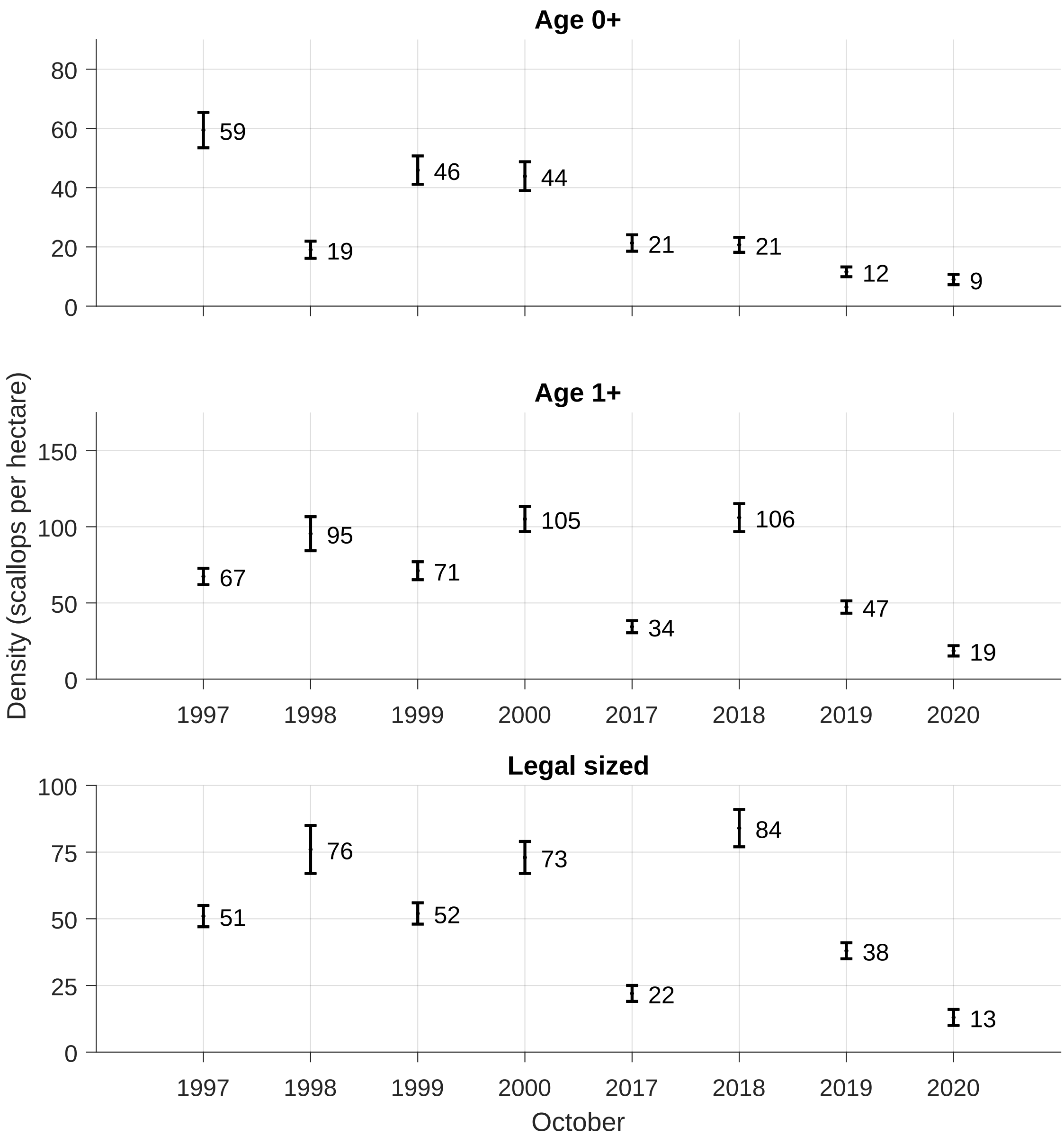

Figure 3.5: Annual mean modelled densities per hectare by year for age 0+, 1+ and legal sized scallops from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

3.2 Model outputs

3.2.1 Model parameters

Parameters estimated in the model are listed in Table 3.1. Where possible parameters were estimated within the model. MCMC parameter distributions are shown in Figure B.5 and the negative log likelihood MCMC trace is shown in Figure B.6

Table 3.1: Parameter estimates for the six main parameters from the median MCMC parameters

Parameter	Estimated value (s.e.)
Virgin recruitment R_0	2.1114×10^9 (0.13046×10^9)
Steepness h	0.2308 (0.0045)
Amplitude of seasonality a	0.2952 (0.0349)
Closure effect on January q_{Jan}	0.3231 (0.0692)
Von Mises mode of monthly recruitment θ	2.1047 (0.2947)
Von Mises variance of monthly recruitment κ	1.0342 (0.1733)

3.2.2 Biomass

The estimated 2020 spawning biomass was 12% of unfished spawning biomass with 95% confidence interval of 8–18% (Figure 3.6). The result suggested the 2020 region 3 spawning biomass was below the limit reference point of 20% (upper bound of 18%).

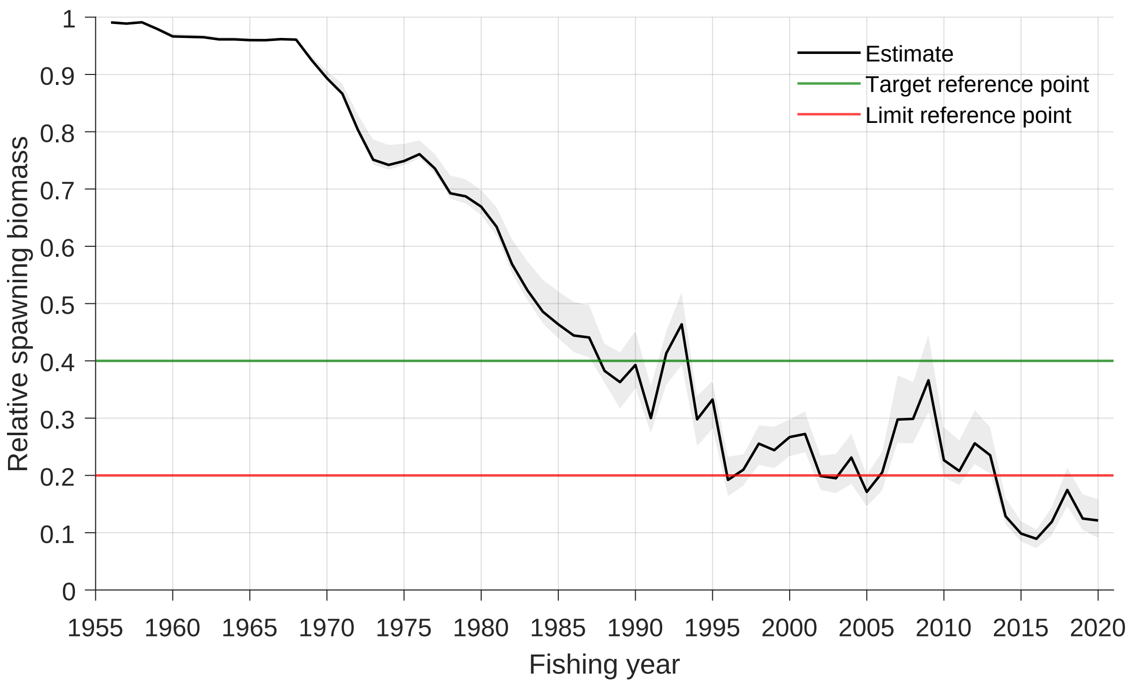

Figure 3.6: Annual spawning biomass ratio (± 95% CI) 1956–2020 on the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

3.2.3 Harvest targets

Maximum sustainable yield occurred at biomass of 44% of unfished biomass (Table 3.2). The potential maximum sustainable yield at 44% biomass is 353 t per year, with effort of about 100 000 effort units.

Table 3.2: Current and target harvest indicators for the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)—95% confidence intervals are shown in brackets

Indicator	Result
2020 spawning biomass ratio	12% (8–18%)
2020 harvest (tonnes meat)	100 t
Average 5 year harvest 2016–2020	158 t
2020 scallop effort units	118 635 eu
Harvest proportions	All commercial otter-trawl
B_{MSY} (relative to unfished)	44%
Potential harvest at B_{40} (relative to unfished)	350 t (321–411 t)
Boat-days to maintain B_{40} (relative to unfished)	1996 boat-days (1746–2296 boat-days)
Effort units to maintain B_{40} (relative to unfished)	109 780 eu (96 030–126 280 eu)

The forward projection scenarios are shown in Figure 3.7. With fishing effort of 275 000 effort units (or 5000 boat-days), the spawning stock did not recover. The projections estimated that with current fishing effort of 118 635 eu, spawning biomass increased but did not reach levels of 40% unfished spawning biomass by 2040. A reduced effort scenario of 80 000 eu produced similar results. Under zero fishing effort, i.e. no fishing, the spawning stock rebuilt to levels of 40% unfished spawning biomass in 13 years.

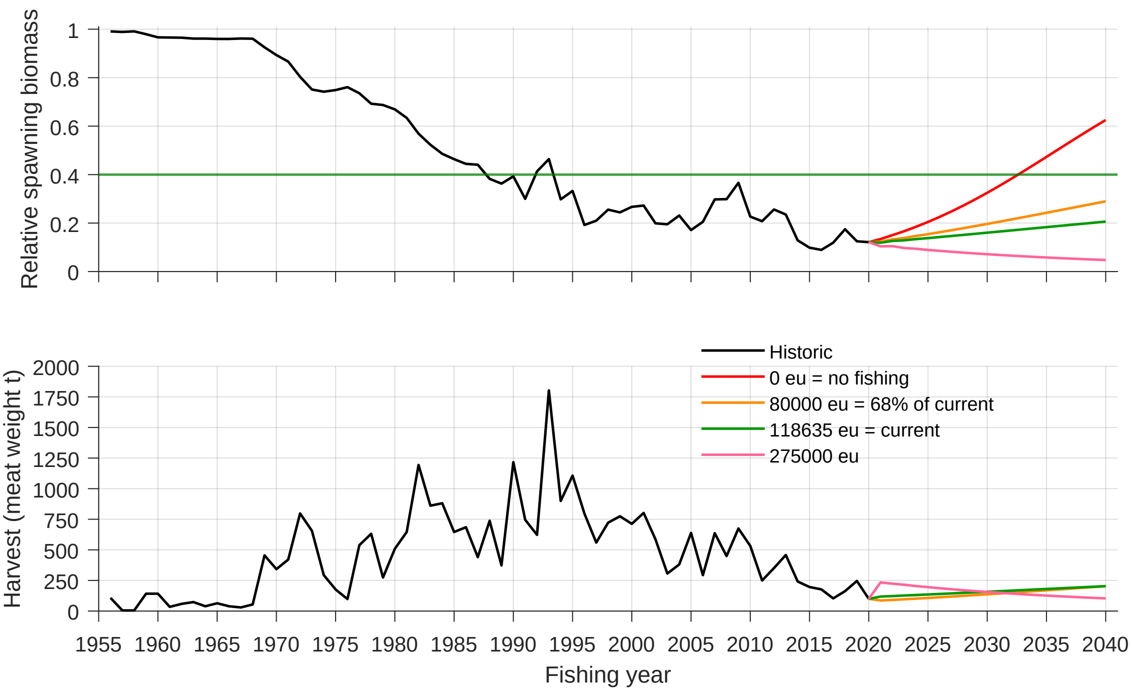

Figure 3.7: Forecasts of annual spawning biomass and harvest from the saucer scallop fishing ground between Yeppoon and Hervey Bay (region 3)

4 Discussion

4.1 Stock status

Spawning biomass ratios in 2020 were still below the limit reference level of 20% and thus the scallop fishery remains overfished. Model projections indicated that the only scenario that would lead to 40% spawning biomass within 15 years in the path to achieve the *Queensland sustainable fisheries strategy 2017–2027* (Queensland Government 2020) ecological objectives was the scenario with no fishing.

4.2 Performance of the population model

There was model convergence (maximum likelihood estimates), and satisfactory goodness of fit to the trends in data. However, it is noted, the model's structures and settings of the model could not predict all catch rates or densities perfectly. This indicates some variance in the data remained unexplained. Estimates of steepness were close to the theoretical (linear) low limit of 0.2. Therefore, estimates of steepness and virgin recruitment were highly correlated. Further work is required to investigate low steepness, possible hyperdepletion in early catch rates and behaviour of other recruitment equations such as the Ricker form (Haddon 2001).

4.3 Environmental influences

Statistical analyses in O'Neill et al. (2020) focused on measuring associations between catch rates of scallops and two variables: sea surface temperature (SST) and chlorophyll (Chl-a). Above average winter SST was negatively associated with scallop catch rates during the next season. Chlorophyll associations were inconsistent.

Results in O'Neill et al. (2020) showed significant effects of rising winter SST on natural mortality. However, it was unclear if this relationship was a primary cause of the scallop population decline, or a coincidental long-term association. The SST data were confounded with abundance, with SST rising at the same time that abundance was falling. As a result, any change in abundance maybe may have been overly ascribed to SST, rather than to other elements such as another undocumented environmental effect, or a greater effect of fishing than the model estimated.

In addition, the scale of increase in sea surface temperatures (SST anomalies) over years was not large (up to one degree Celsius), and Queensland scallops have not suffered high sea surface temperature anomalies between two and four degrees Celsius like experienced in Western Australia in 2010–2011 which had a catastrophic impact on scallops.

The modelled consequence of increased SST in O'Neill et al. (2020) was for reduced scallop survival, abundance and fishery yield. This result, in the context of future fishery management and harvest strategies, suggested effort control rules might need allowance for high natural mortalities.

4.4 Recommendations

4.4.1 Monitoring

The government and industry need to continue the annual fishery independent abundance surveys to validate stock status and to optimise management procedures. A rigorous survey design is crucial. Digital instruments are required to better measure the depth, position and swept area of each survey trawl and vessel, and improve calibration measures between survey vessels. Camera-based surveys of the seafloor result in higher detection efficiency of Atlantic sea scallops compared to dredge surveys, and may also be more efficient than the trawl method used in Queensland surveys (NEFSC Sea Scallop Working Group 2018). Experiments designed to measure scallop catchability would improve interpretation of each year's survey densities. If completed, recommended biological catches can come directly from the survey information.

Sea surface temperature/ocean anomalies should be monitored and assessed. The deployment of site-specific sea-floor water temperature sensors should be considered.

4.4.2 Management

The model results provide support for additional Queensland Government management interventions that control fishing efforts to increase scallop biomass.

The SRAs should remain closed until spawning recovery is measured. If SRAs are reopened in the future, then the length of closed seasons needs to be re-evaluated (how long they need to be open and closed). It appears scallop abundance increases proportionally to the closed duration, and past modelling suggested closure times of at least three years (Campbell et al. 2010b).

Fishing effort in region 3 needs to be reduced from the current effort of 118 635 units in order to allow the recovery of scallop stocks. The recent decline in the stock biomass from 2018 to 2020 highlights the need to reduce the level of fishing mortality (effort units) to a level that allows the stock to rebuild within acceptable and biologically relevant timeframe. If spawning levels are at 40%, then the possible yield from the scallop fishery is 350 t. Without a large reduction in effort units it is estimated that the stock will not recover to 40% initial biomass within the next twenty years.

4.4.3 Assessment

The time-series data on trawl fishing power through compulsory logbook gear sheets should be reviewed. The impact of improved technology is an important consideration for standardising catch rates. Some fishing technologies have been included in this assessment, but others have not due to lack of information (e.g use of by catch reduction device, use of turtle exclusion device, net size). In many fisheries, there are advances in technologies in addition to those assessed in this report. Fishing effort continues to change with ongoing technological advancement.

The time series of standardised catch rates should continually be improved. Validation of catch data is a priority for fisheries management across all commercial fisheries. Improved information on hours fished, the fishing gear used, and precise fishing location information (through VMS and TrackMapper) will enable modelling of the changing dynamics of fishing and produce better standardised catch rates. Dedicated work is also required to analyse the Htrawl catch rate data for the years 1977–1987. The quality of the HTrawl data may improve by further checking and verification.

The estimates of natural mortality from the Brownie et al. (1985) Model 1 method in Courtney et al. (2020) showed that there was a seasonal variation in M. The stock model could be extended to incorporate a changing M over time, instead of a constant M.

Further work on model projections and management strategy evaluations may be required.

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Appendix A Model inputs

A.1 Vessel configurations

Information on vessel gear and technologies from the catch rate data set showed a number of continuing trends, in agreement with those reported in the 2020 stock assessment (Wortmann et al. 2020).

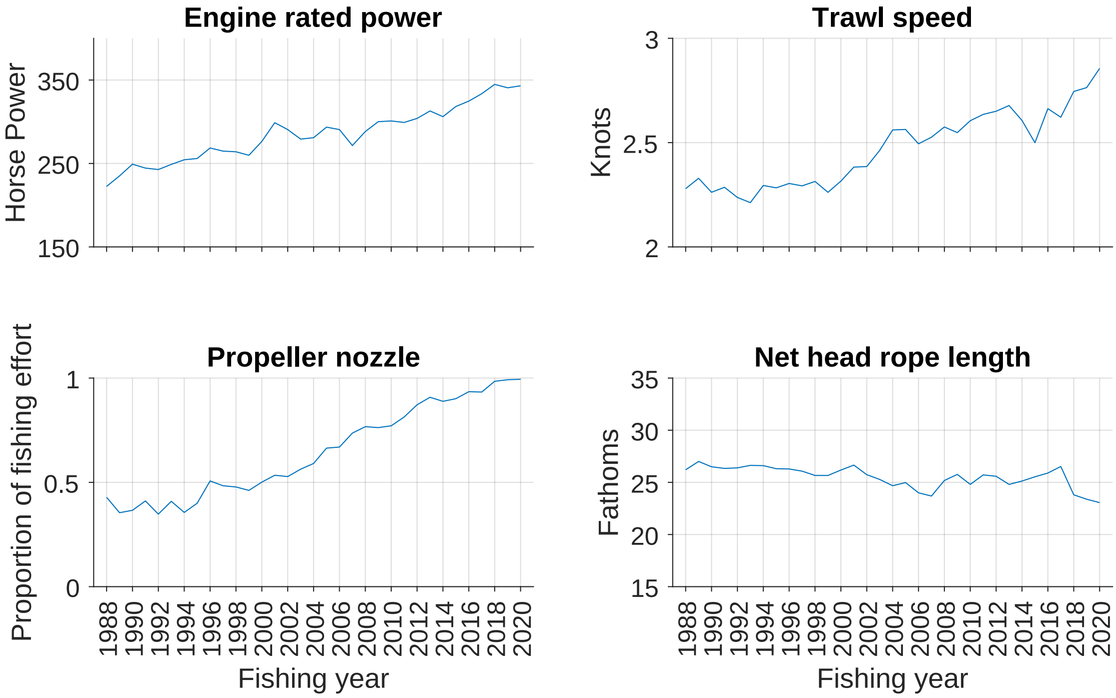

Figure A.1: The fleet average engine rated power, trawling speed, use of propeller nozzles and net size by fishing year—averages were weighted according to the number of days fished by each vessel in each fishing year

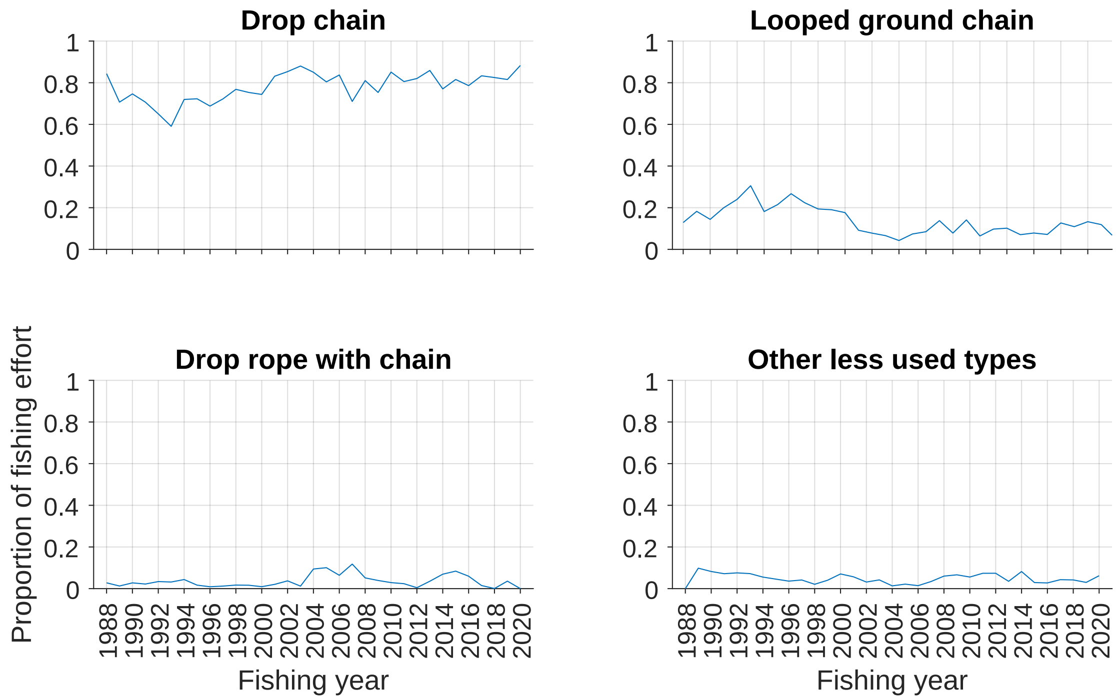

Figure A.2: The proportion of total annual fishing effort by vessels using various ground gear configurations

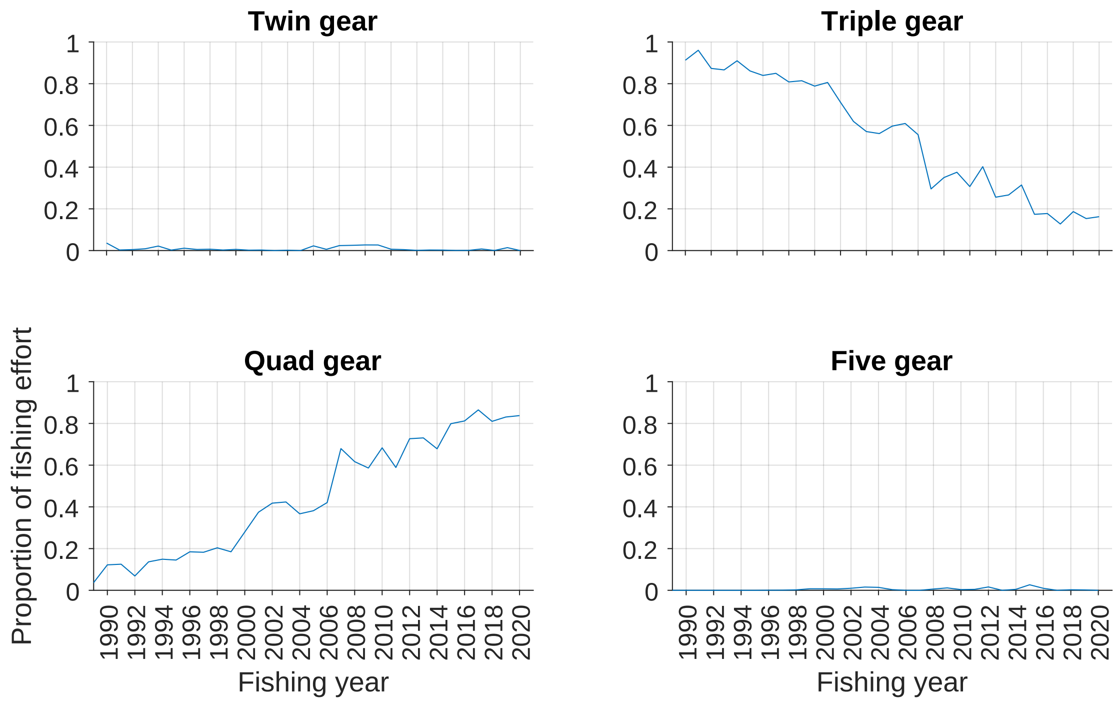

Figure A.3: The proportion of total annual fishing effort by vessels using various net configurations

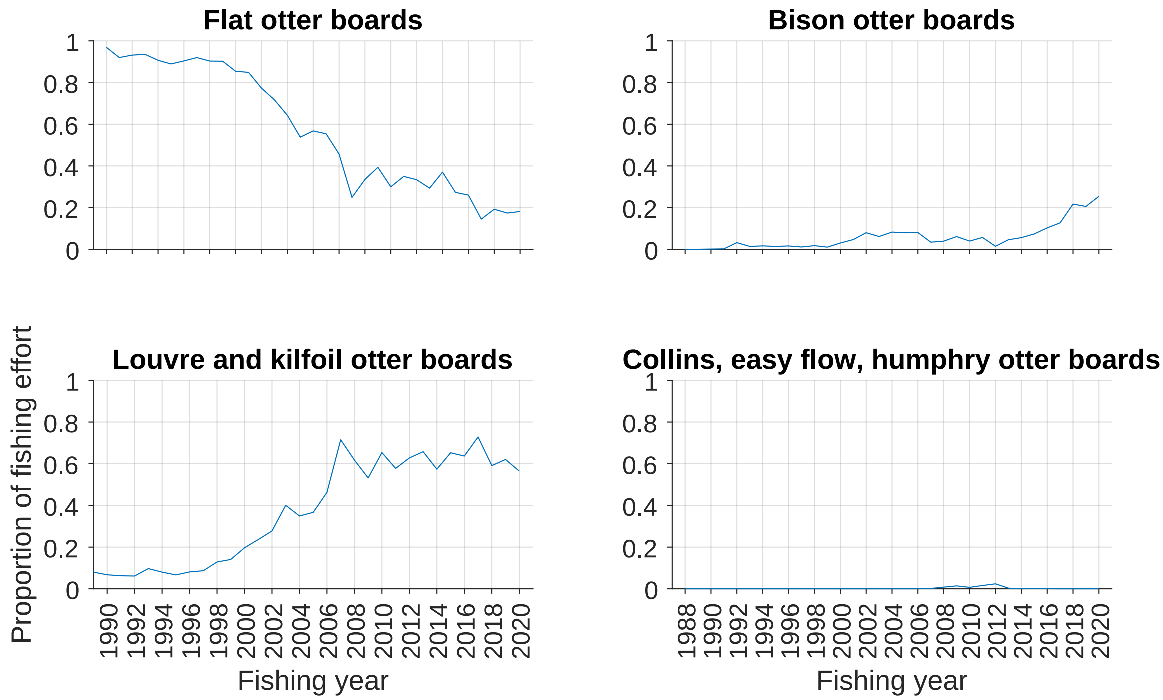

Figure A.4: The proportion of total annual fishing effort by vessels using various otter board configurations

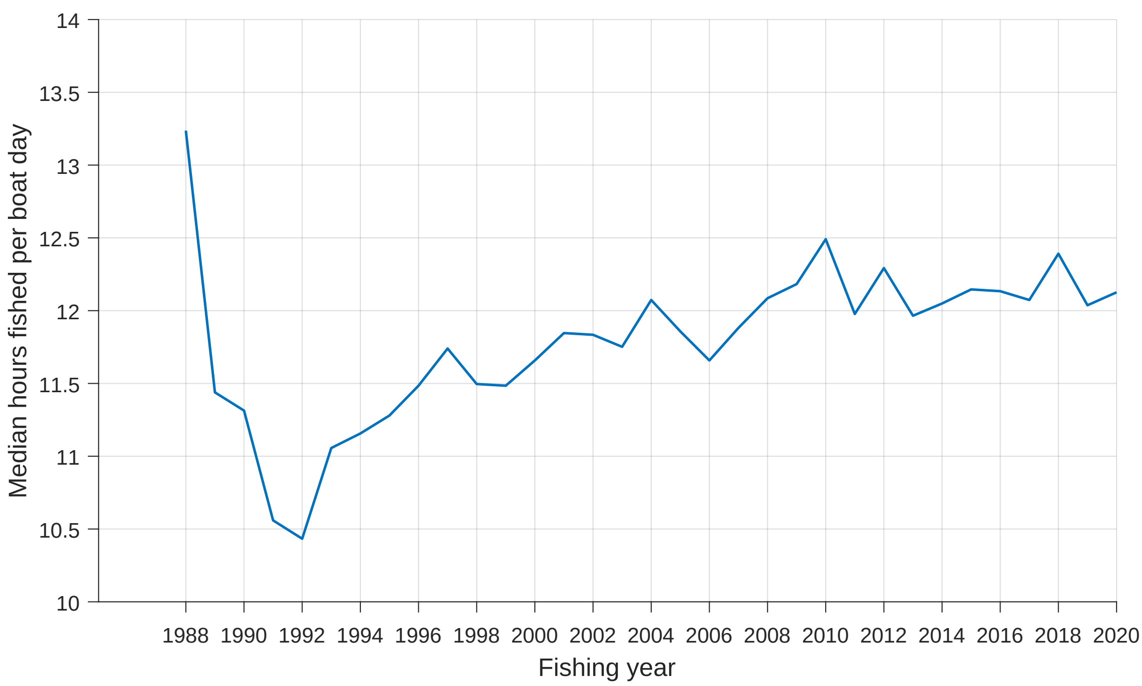

Figure A.5: Median hours fished per boat-day from the linear mixed model data

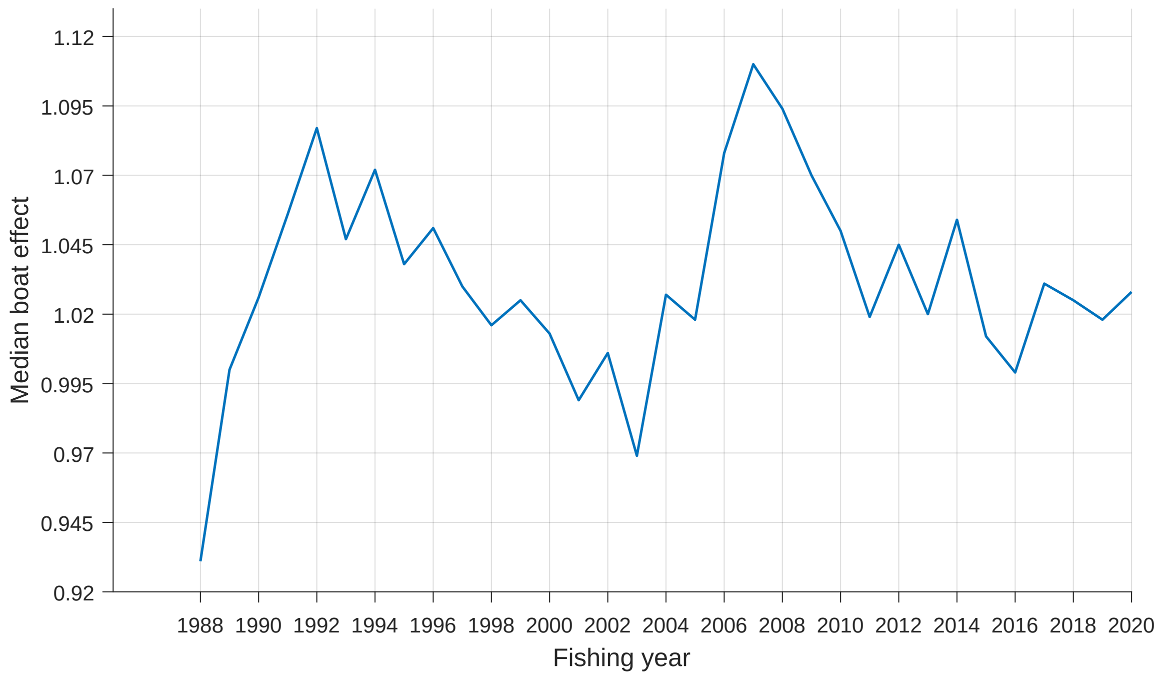

Figure A.6: Median annual boat effect from the linear mixed model data

A.2 Fishing power

The 1988–2020 catch rate standardisation measured annual changes in fishing power, based on fixed and random model components (O'Neill et al. 2007). The product was a measure of annual fleet fishing power, scaled as the proportional change relative to 1989.

Gear changes, technology upgrades and hours fished were the fixed terms from the model. For the fixed terms, the variability in fishing power was represented by the dashed line in Figure A.7, where fishing power increased by about 16% from 1989–2020. This annual increase associated with vessels having higher HP, increased use of GPS and sonar, and quad trawl gear.

The overall fishing power estimate including both gear and vessel terms, showed that fishing power increased by about 22% from 1989–2020. The increase in fishing power from 2019–2020 is likely due to worse boats leaving the scallop fishery (Figure A.6).

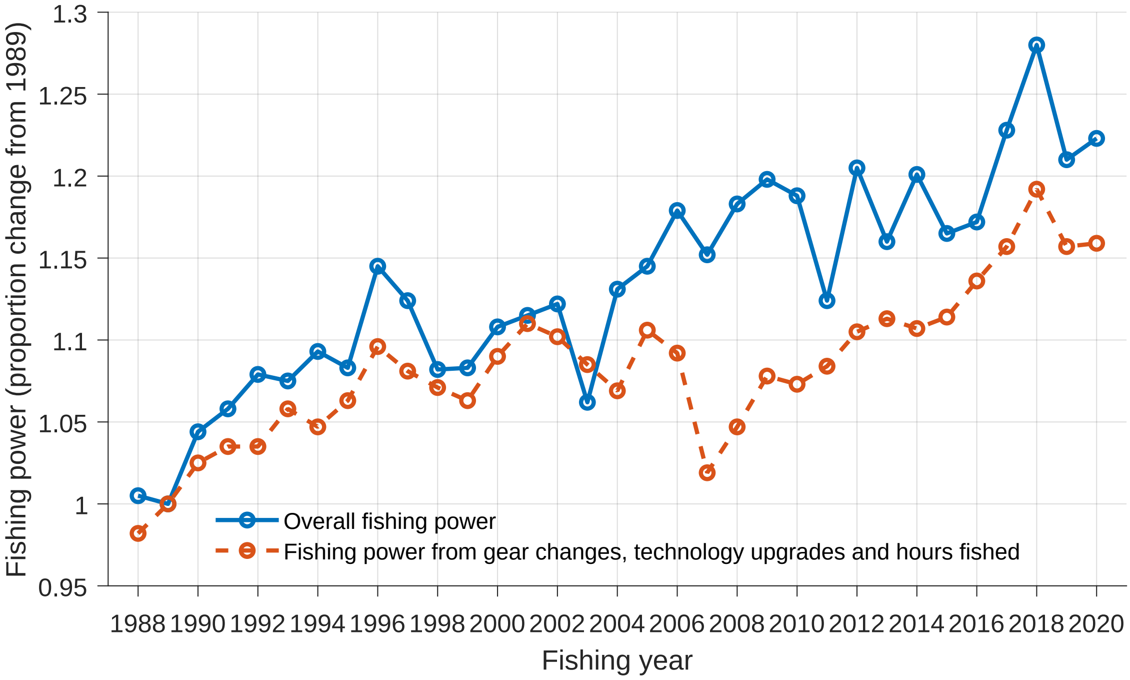

Figure A.7: Annual fleet fishing power on saucer scallops

Appendix B Model outputs

B.1 Catch rate diagnostics

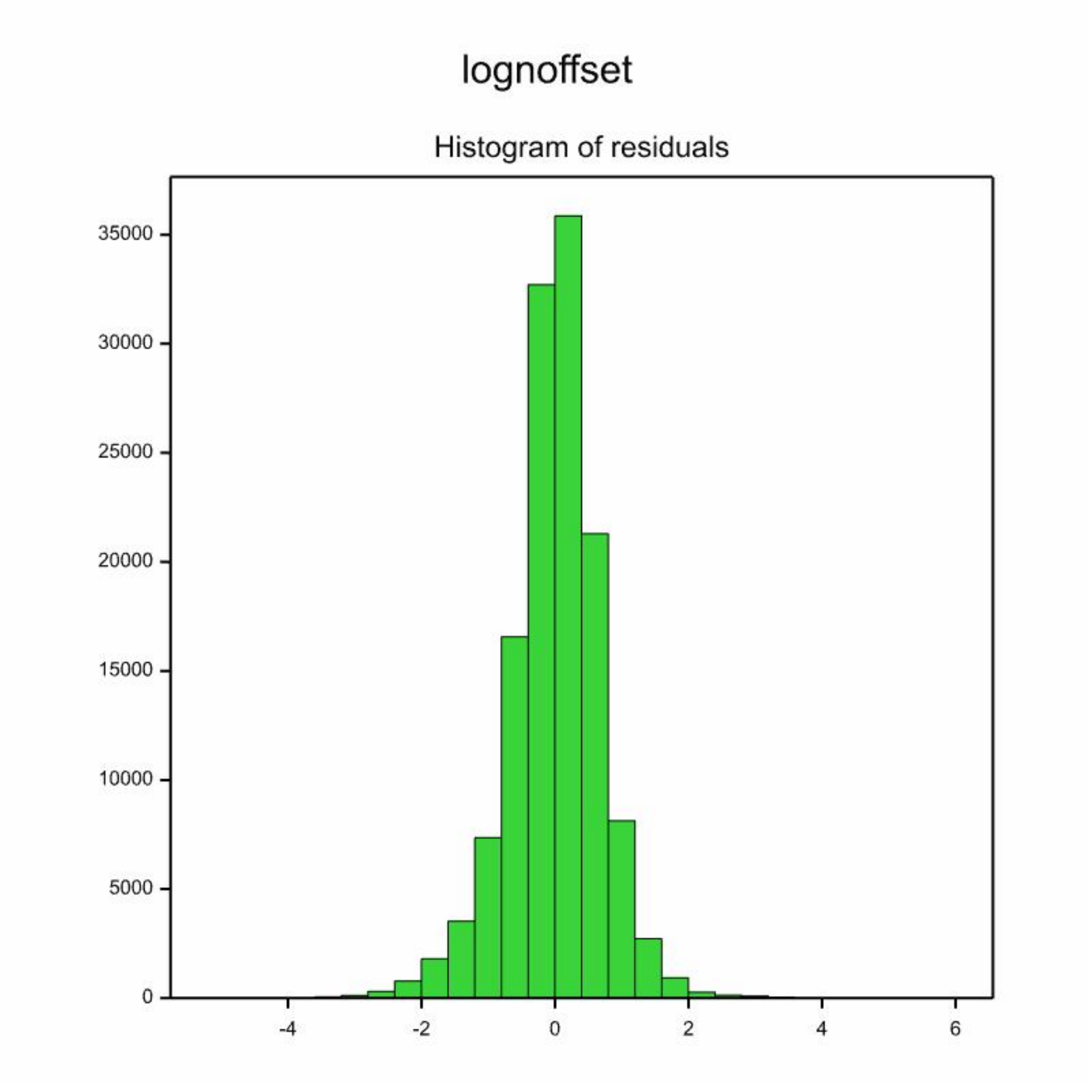

Figure B.1: Residuals for the saucer scallop catch rate analysis 1977–2020

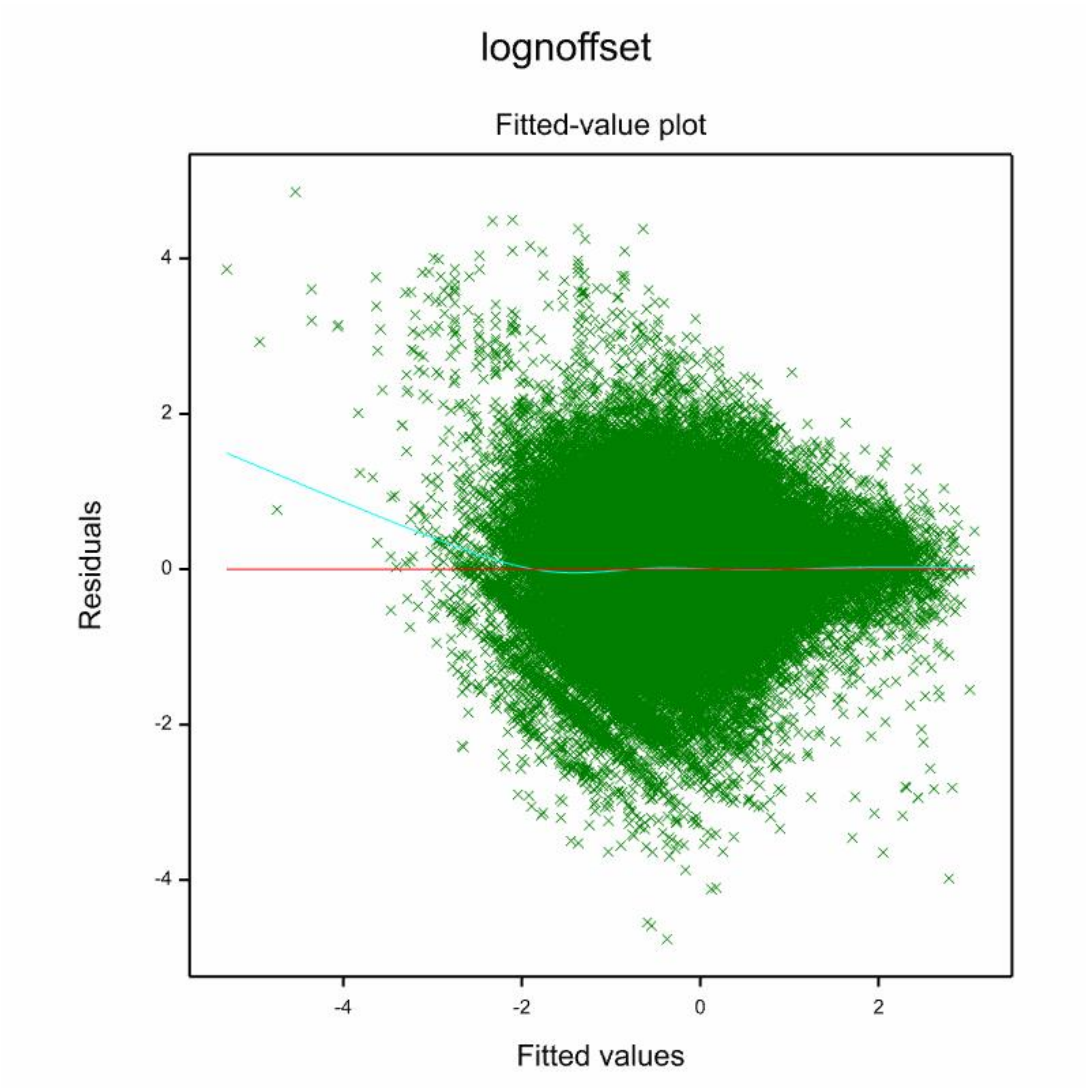

Figure B.2: Fitted values for the saucer scallop catch rate analysis 1977–2020

B.2 Model fit

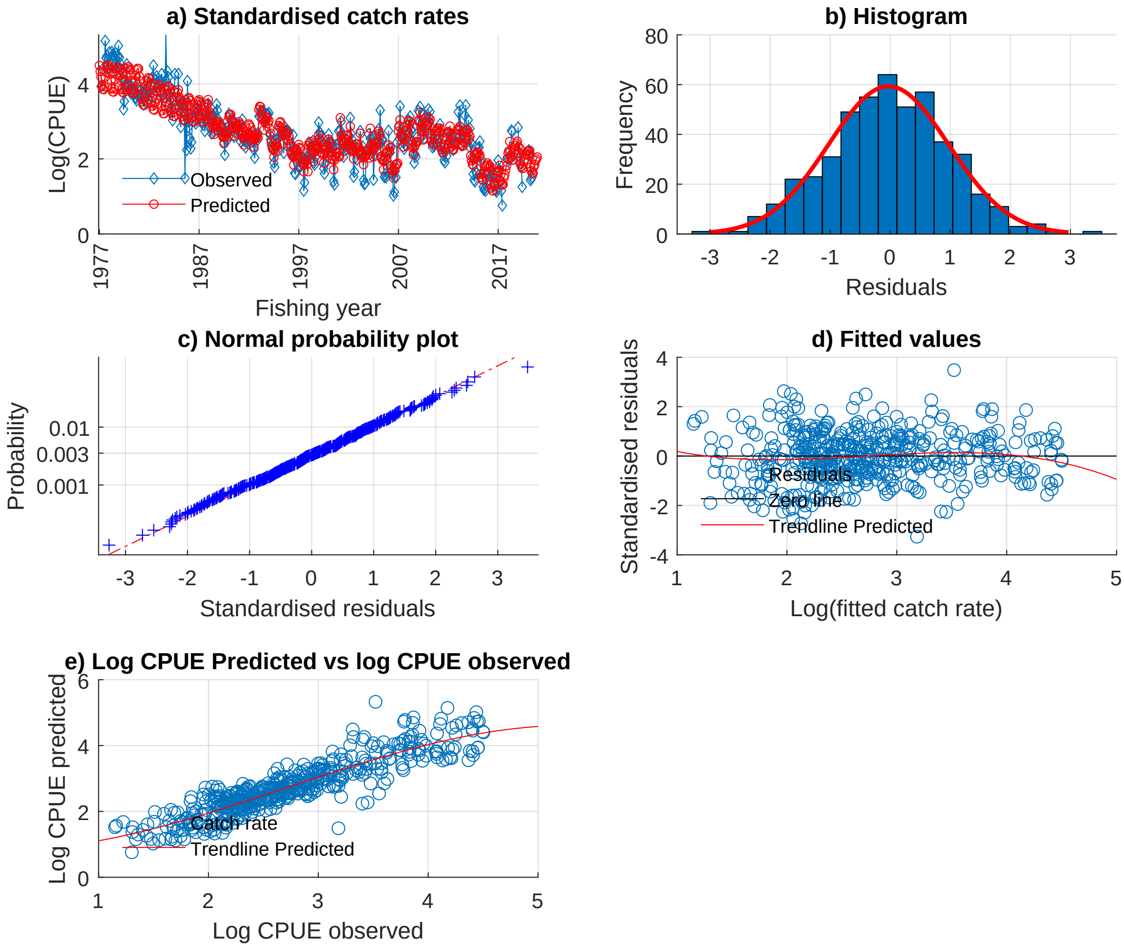

Figure B.3: Catch rate fit-diagnostics

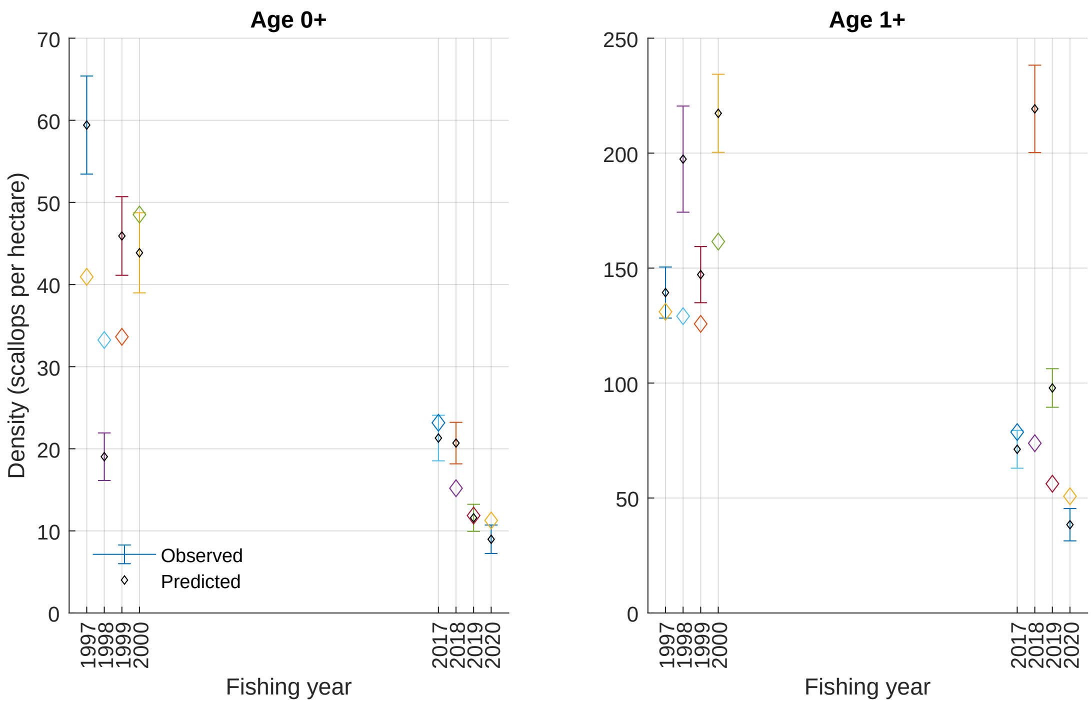

Figure B.4: Age 0+ and 1+ densities from the model (± one standard error)

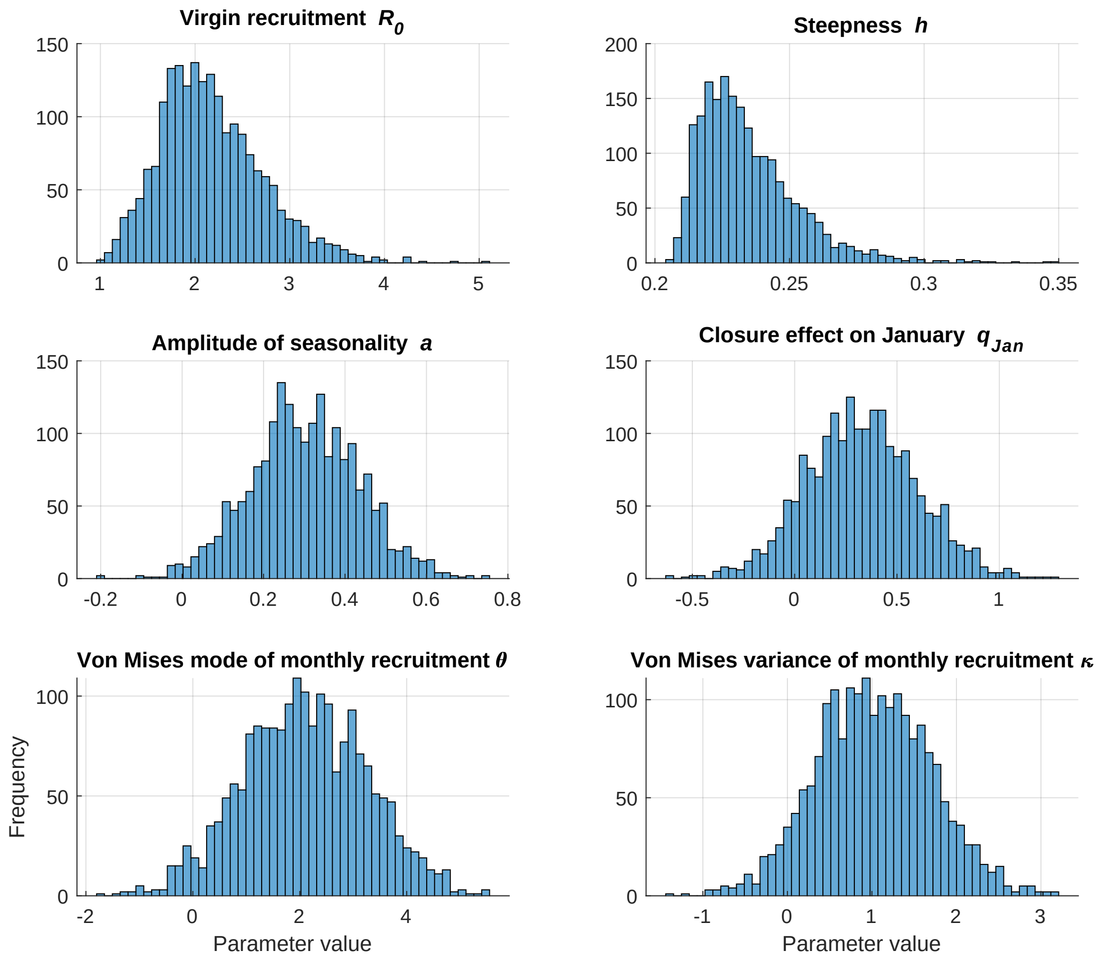

Figure B.5: MCMC parameter estimates for the six main parameters from the model

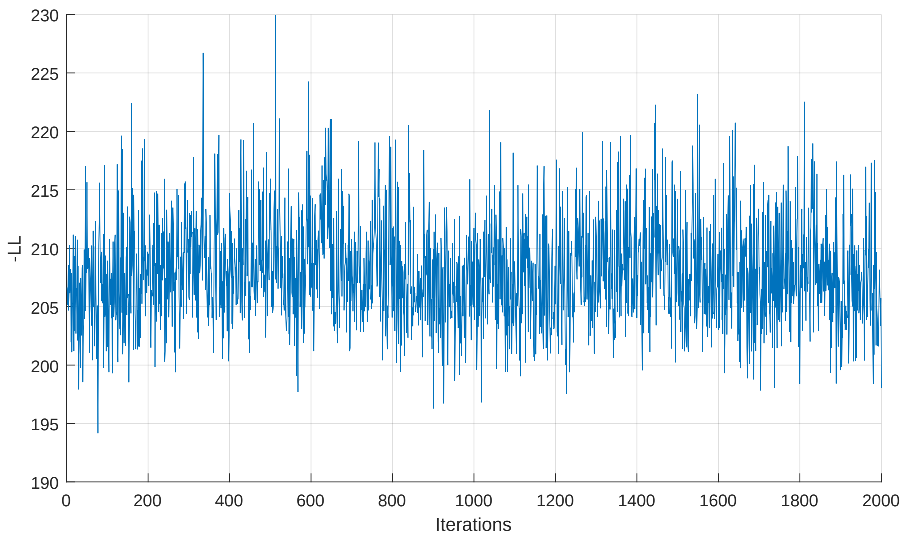

Figure B.6: MCMC –LL trace for the model