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

2021

Queensland Government

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Summary

This stock assessment indicates that biomass declined between 1956 and 2016 to 10% unfished biomass. In 2021, the stock level was estimated to be 15% unfished biomass (95% confidence interval 10–29%).

The Queensland east coast Ballot's saucer scallop (*Ylistrum balloti*, formerly *Amusium balloti*) is a marine bivalve mollusc with a hinged shell. They are mainly found between 22° South and 27° South in shelf water depths of 20 to 60 metres. 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.

Saucer scallop are a largely sedentary broadcast spawner that form spatially distinct population aggregations where the habitat is suitable. In general these aggregations are reproductively connected, however there is some evidence to suggest that saucer scallops on the fishing ground east of K'gari, Fraser Island, are less connected to those on the fishing grounds between Yeppoon and Hervey Bay.

This stock assessment used an age structured population model with a monthly time step. The model incorporated data spanning the period from 1956 to 2021 including total annual meat weight harvest (1956 to 1987), the Queensland historical trawl database (1977 to 1987), Queensland commercial logbook data (1988–2021), and survey data providing densities of saucer scallop in two size classes (1997-2000, 2017-2021). The saucer scallop fishing year is defined as November of the preceding year to October of the named year (that is, fishing year 1997 is November 1996 to October 1997) and all references to year are to fishing year.

This stock assessment builds on previous assessments that estimated the biomass at 5-10% and 9% in 2016 and 2018 respectively. This assessment estimated the biomass to be 15% in 2021. It includes updates to the input data but keeps the methodology in line with the 2018 assessment.

Over the last 5 years, 2017 to 2021, total harvest averaged 235 t (Figure 1).

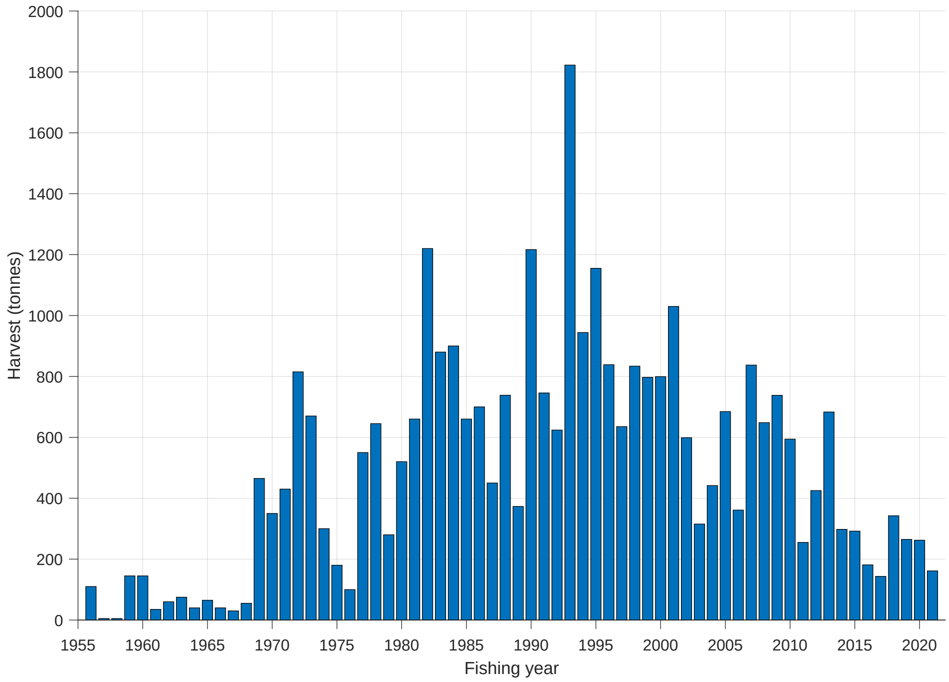

Figure 1: Annual estimated saucer scallop harvest from 1956 to 2021

Commercial catch rates were standardised to estimate an index of saucer scallop abundance through time (Figure 2). The unit of standardisation was baskets of saucer scallop per 'boat-day', defined to be a single day of fishing by a primary vessel. Year, month, area (Yeppoon, Bustard Head, Hervey Bay, K'Gari), spatial grid, vessel, hours fished, engine horse power, vessel speed, use of sonar, use of GPS, net type, ground gear type and combinations of these were included explanatory terms.

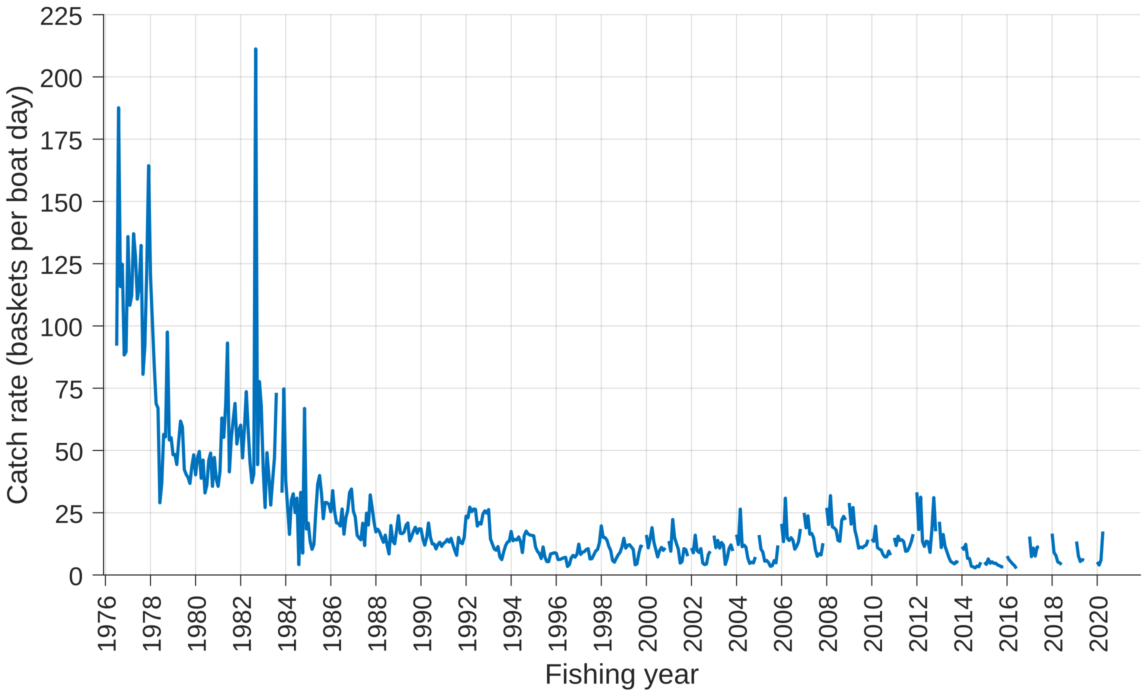

Figure 2: Standardised monthly catch rates from 1977 to 2021

Survey density data were also standardised, to estimate annual densities of two age groups of saucer scallop (Figure 3). The unit of standardisation was the number of saucer scallops per hectare.

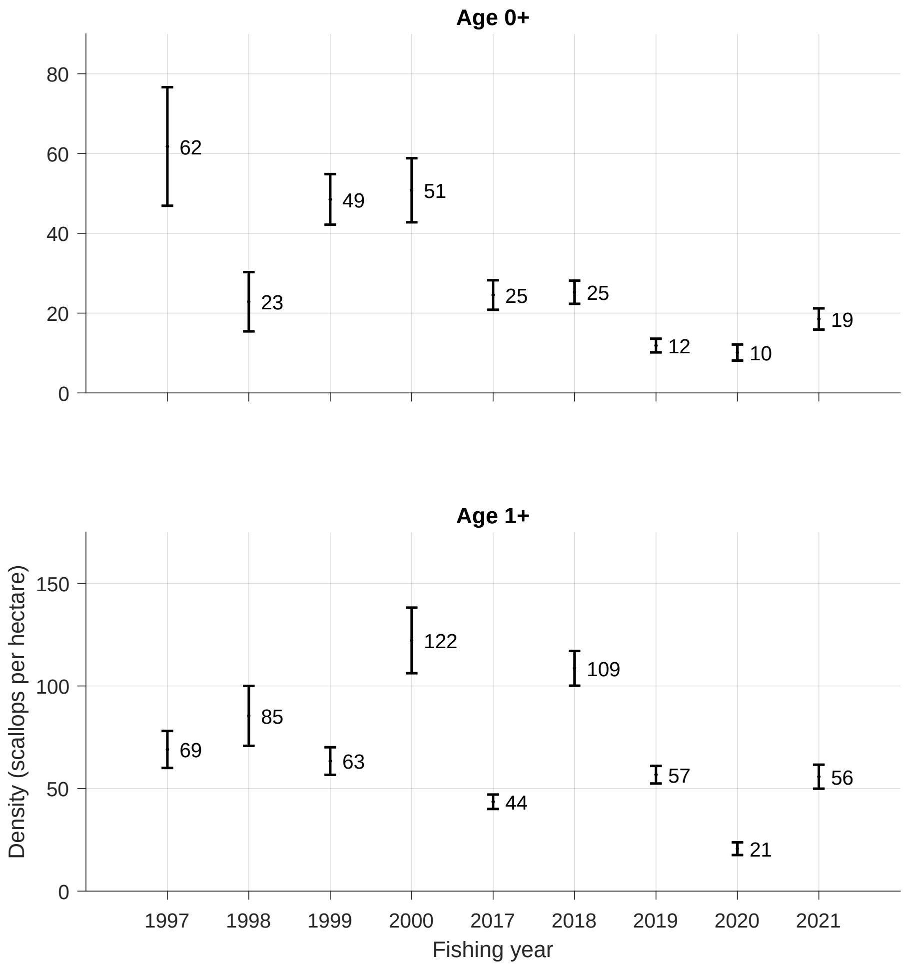

Figure 3: Mean modelled scallop densities per hectare

Model results indicate that biomass declined between 1956 and 2016 to 10% unfished biomass. In 2021, the stock level was estimated to be 15% unfished biomass (95% confidence interval 10–29%) (Figure 4).

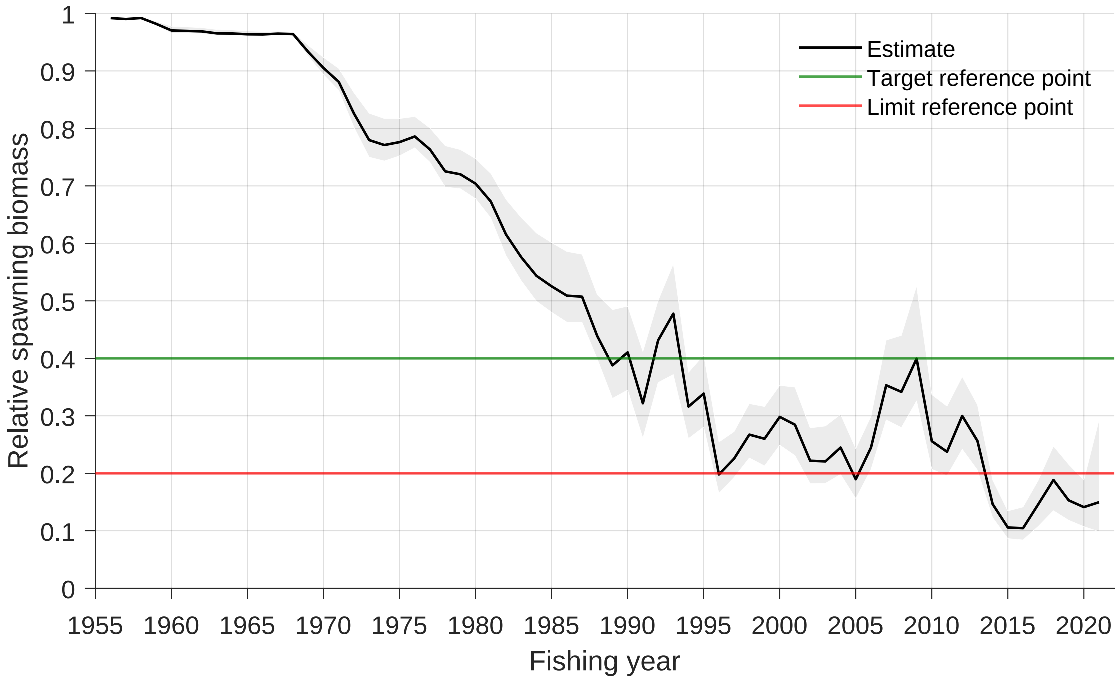

Figure 4: Spawning biomass ratio (±95% CI) from 1956 to 2021

The harvest consistent with a biomass ratio of 40%, the biomass target for this fishery, was estimated at 363 t. The recommended biological harvest in the 2022 fishing year is 0 t, to achieve the trawl fishery biomass target of 40% unfished. At 0 t harvest it is estimated that it would take 10 years to rebuild to 40%.

Table 1: Current and target indicators

Indicator	**Estimate**
Current (2021) spawning biomass (relative to unfished)	15% (10–29%)
Spawning biomass at maximum sustainable harvest	44%
Current (2021) harvest	161 t
Sustainable harvest at spawning $B_{40\%}$	363 t (303–432 t)
Maximum sustainable harvest	366 t
Proposed harvest (2022) to achieve $B_{40\%}$ target	0 t
Time to reach target	approx. 10 years

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This report is an update of Wortmann (2021) 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 × 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	The Queensland historical trawl database containing 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 (Southern Inshore trawl region)
Region 4	The scallop fishery for the K'gari fishing zone, Fraser Island (Southern Offshore trawl region)
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. 2010; 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 appear to 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.

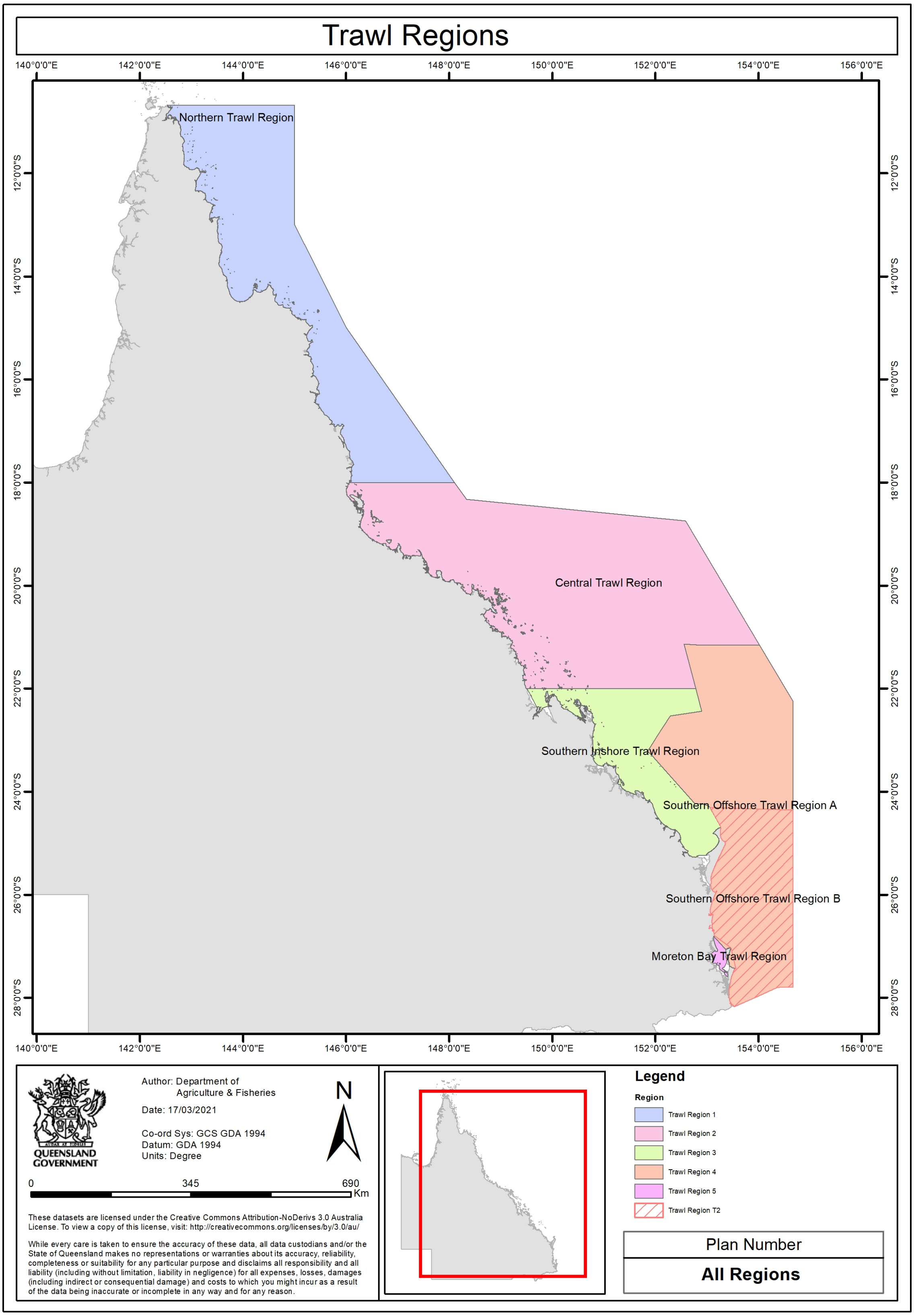

Figure 1.1: East coast trawl fishery divided into five management units (Department of Agriculture and Fisheries 2019)—the saucer scallop fishing sector is the southern inshore trawl region, region 3, south of 22° S to Hervey Bay (shaded green)

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) in region 3
	November 2020	Annual effort cap of 80 000 eu (1454 boat-days) in region 3
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
	November 2021	No take scallops in southern inshore and central trawl regions, southern offshore region open for scallop fishing 20 January–1 May

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. Previous assessments estimated the spawning biomass at 5–10% and 9% in 2016 and 2018 respectively (Yang et al. 2016; O’Neill et al. 2020).

A stock assessment was conducted in 2021 analysing data through to the end of the 2020 fishing year (Wortmann 2021), however it considered the Southern Inshore trawl region only, so it is not directly comparable.

This stock assessment estimates spawning biomass for region 3 (Southern Inshore trawl region) and region 4 (Southern Offshore trawl region) combined, in line with the 2016 and 2018 assessments. It includes updates to the input data but keeps the methodology in line with the 2018 assessment (O'Neill et al. 2020).

2 Methods

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. Data sources were used to determine catch rates, density of scallops for two age classes, and create annual harvests. Data sets were compiled by fishing year[1] and all references to year should be assumed to be fishing year. The assessment period began in 1956 up until and including 2021 based on available information.

Table 2.1: Data inputs for the population model

Type	Fishing year	Source
Commercial	1956–1987	Total annual meat weight harvest (Dredge 2006)
	1977–1987	Historical trawl ('HTrawl') catch rate data (O'Neill et al. 2005)
	1988–2021	Compulsory CFISH logbook data collected by Fisheries Queensland
Fishery independent survey	October 1997–2000, 2017–2021	Agri-Science Queensland survey data FRDC project 2017-048 (Courtney et al. 2020)

2.2 Harvest

Historical commercial catch data 1956–1987 was calculated from data from Dredge (2006). Section 3.1 of O'Neill et al. (2020) outlined the methods used to calculated the historical catch data. Ruello (1975) reported that the trawl fishery for saucer scallops commenced in the mid-1950s off the central Queensland coast, between 23° S and 25° S. Dichmont et al. (1998) reported that fishing of scallops commenced in the mid-1950s, when prawn trawlers worked out of Hervey Bay taking appreciable quantities.

Between 1956 and 1977 there were small amounts of scallop harvest. This was catch data only, as effort data was not recorded then. The scallop fishery did not start seriously until the late 1960s when export markets for the product were identified. The fishery grew during the 1970s to a mature operation in the 1980s and may have been overexploited by the mid- to late 1990s (Dredge 1990). Regardless of the amount of scallop harvest between 1956 and 1977, it was still harvest and therefore, cannot be excluded in the scallop stock assessment as the stock was not in a virgin state.

While more than 90% of average annual landings from the Queensland fishery have been taken between 23° S and 25° S, grounds in the vicinity of Hydrographer's Passage (22° S) and off Townsville (19° S) receive intermittent recruitment and occasionally produce substantial quantities of saucer scallops (Dredge 2006) (Appendix A.1). These areas do not form part of region 3 and region 4 and were not included in model input data. For these regions to be included in the stock assessment the fishery-independent surveys (Courtney et al. 2020) would need to include these areas.

[1] 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.

Commercial catch data 1988–2021 was from CFISH logbooks. The logbook system consists of daily harvests (landed baskets of saucer scallops) from each individual fishing operator (license) since 1989. In addition to landed baskets, logbooks also record the location of the catch (30 minute or 6 minute grid identifier). The commercial catch data included catch from the SRAs and was from logbook records for baskets per fishing year per fishing month for region 3 and region 4.

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) (Courtney et al. 2020). The survey focused on scallops grouped by age (0+ or 1+, depending on their size) in October of 2021. 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 scallop trawl survey was based on a stratified random design that was first implemented in 1997 (Dichmont et al. 2000). From 1997–2000 the survey was comprehensively implemented, but from 2001-–2006 the number of strata and sample sites were reduced, and the survey ceased in 2006. In 2017 the full survey design was reintroduced and included two additional strata in the southern part of the fishery (K'gari) (Courtney et al. 2020).

Survey density data was for all surveys done in region 3 and region 4, including in the SRAs. The age 0+ survey data informed recruitment in the model, thus recruitment from the SRAs was accounted for in the model.

Justification for the timing of the fishery independent survey comes from (Dichmont et al. 2000). Early October was chosen to optimise the catch of 0+ recruits (less than 78mm shell height) following the winter spawning (June-August), before the main fishing season. Early October has favourable seasonal weather conditions required for a trawl survey. Undertaking the survey in October also enhances the availability of vessels for chartering, as most vessels are not fishing at this time due to a regional trawl closure. The timing of the survey was centred around the neap tides to minimise the low scallop catch rates during the strong tidal currents associated with spring tides.

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 and the assessment in Wortmann (2021) 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 survey data for the strata T29 and T30 and surveys done during the day for the years 1997–2000 were excluded from GLM because in the early years the calibration was done during the day in sites with known scallop aggregations, wheres for the later years (2017–2021) the calibration was done in randomly selected sites, thus inflating the early survey density estimates. This filtering was not applied in previous stock assessments.

The adjusted means from the GLM 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 K'gari, including scallop replenishment areas, in the month of October for the years 1997–2000 and 2017–2021. 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).

Detailed results from the latest survey, completed in October 2021, are presented in Appendix D.

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), Wortmann et al. (2020) and Wortmann (2021).

Fishing trips do not differentiate between scallop and bug trips, and all scallop catch data was used whether fishing for bugs or scallops to calculate the scallop catch rate. A target factor for bugs or scallops was explored in the catch rate standardisation in Appendix A.5. The definition of whether a fishing day was targeting bugs or scallops was based on weight caught of the group, and the results using this definition did not change the catch rate trend. The new trawl commercial fishing logbook will have the option for fishers to nominate scallop and bug fishing trips.

Low scallop catch rates, even if the fishers were targeting bugs cannot be omitted, because it still provides important information on the stock biomass. Furthermore, excluding low scallop catch rate data may artificially inflate the scallop catch per unit effort.

A list of the filters applied to the CFISH data to obtain the data for catch rate standardisation are listed in Appendix A.2. When the SRAs were open and logbook records recorded catch in the SRAs, these records were included in the standardisation. Area was a factor (Yeppoon, Bustard Head, Hervey Bay and K'gari) in the standardisation model and influenced the catch rates.

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 1988–2021 and changes in fishing power from gear changes, technology upgrades and hours fished from 1988–2021 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 1988–2021 and 1977–2021. The 1977–2021 analysis used fishing power parameter estimates from the first 1988–2021 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 1988–2021 (analysis 3 from O'Neill et al. (2020)) using:

$$\begin{aligned} log(baskets\ per\ boat\ day) = fishing\ year \times fishing\ month \times area + log(hours\ per\ boat\ day) + log(hp) + \\ log(speed) + sonar + gps + nettype + ggear + random(boat\ label\ code) \end{aligned} \tag{2.1}$$

where

- *area* = Yeppoon, Bustard Head, Hervey Bay, K'gari
- *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 1988–2021 were standardised to a modern-day boat. The standardisation factors were:

- Use of GPS and sonar
- Net type of quad gear (Figure A.4)
- Ground gear of drop chain (Figure A.3)
- Hours fished equal to the average of log hours fished for 2007–2020 (12 hours) (Figure A.6)
- Engine power equal to the average 2020 engine power of 343 HP (Figure A.2)
- Boat that matched the maximum annual average boat effect-for this catch rate analysis, this was in 2007 (Figure A.7).

Catch rates were standardized for 1977–2021 using analysis 4 of O'Neill et al. (2020):

$$\begin{aligned} offsetlog = log(hp) * 0.3792 + sonar * 0.1450 + gps * 0.03512 + (nettype.eq.3) * 0.2791 + \\ (nettype.eq.4) * 0.2277 + (nettype.eq.5) * 0.2784 + (ggear.eq.3) * 0.07386 + \\ (ggear.eq.4) * -0.02462 + (ggear.eq.5) * -0.13147 \end{aligned} \tag{2.2}$$

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

$$lognoffset = fishing\ year \times fishing\ month + log(hours\ per\ boat\ day) + +random(boat\ label\ code) + random(grid) \quad (2.4)$$

where

- The coefficients were estimated from the 1988–2021 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.5* is five gear.

Catch rates for 1977–2021 were standardised to the same modern boats setting as above. Fishing year by month trend for January 1977 to October 2021 for region 3 and region 4 was calculated. The result focused on a single *fishing year* × *fishing month* catch rate index.

2.5 Natural mortality

Findings from the tagging study Courtney et al. (2020) indicated the natural mortality rate (M) was significantly higher than previously measured by Dredge (1985). The recent stock assessments (Wortmann et al. 2020; Wortmann 2021) and this stock assessment included an updated estimate of M based on the logistic model developed in Courtney et al. (2020) (i.e., M = 1.461 per year or 0.1217 per month). The natural mortality was assumed constant. The effect of this increase in natural mortality from Dredges estimate was spawning biomass ratios approximately 2% higher.

2.6 Population model

The non-spatial model from O'Neill et al. (2020), Wortmann et al. (2020), and Wortmann (2021) was used for this stock assessment. This model described the scallops as a single stock across region 3 and region 4 combined. No environmental effects were included. The model was an age-based population dynamic model that assessed scallops monthly from the fishing years 1956 to 2021, 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 (MATLAB 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,

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

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,

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

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 $B_t^{(2)}$:

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

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

$B_t^{(1)}$ 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.

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

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

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

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

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

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

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

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

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:

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

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:

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

(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 2002). 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 2021 . 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 792 (i.e. 12 months × 66 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. 2010).
$f_a(\ell)$	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.

Continued on next page

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. (2010) 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

Continued on next page

Table 2.2 – *Continued from previous page*

	Equations and values	**Notes**
$G(\ell, \text{MLS}_t)$	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. 2010). Tumbler use was sporadic in the 1970s, but was utilised from late 1980.
d	3.3%	Discard mortality (Campbell et al. 2010).
A	1 256 473.72 (Region 3) + 231445.4 (Region 4)	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.

Continued on next page

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 Parameter estimation

The parameter estimation process 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 region 4 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 2021 fishing year (closed May–October), and recruitment was deterministic. All effort units were assigned to scallop. The projections were done for levels of fishing effort listed in 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
2021 region 3 effort cap	80 000 eu
2020 region 3 effort cap	118 635 eu
High	275 000 eu

2.6.5 Sensitivity tests

An additional model run was undertaken with input data for region 3 only in order to determine the spawning biomass of the management stock in region 3.

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, 2020 and 2021 fishing years were 342 tonnes, 264 tonnes, 262 tonnes and 161 tonnes (meat weight) respectively for the management stock in region 3 and region 4 combined.

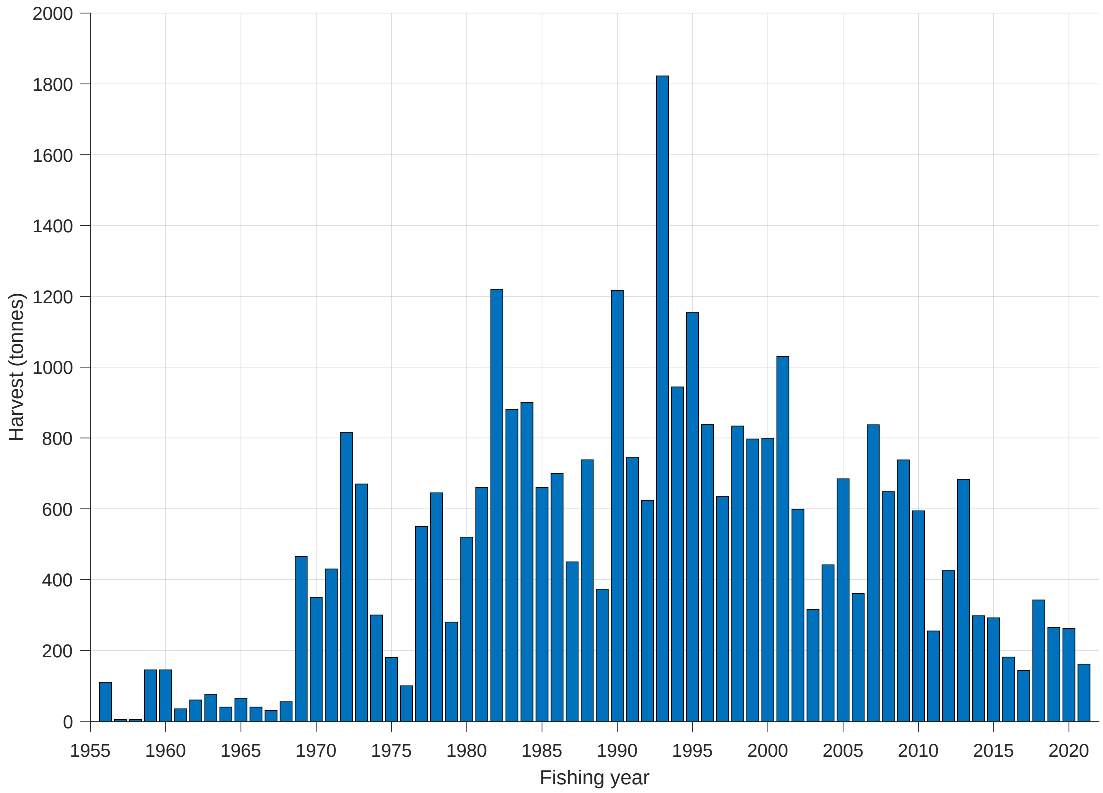

Figure 3.1: Annual estimated saucer scallop harvest 1956–2021

Figure 3.2 shows the typical seasonal change in scallop harvest, with scallop harvests by month for the period 1956–2021. Between 1956 and 1970, a very small amount of harvest was recorded. Since 2002, clear spikes in harvest occurred in the months of November–January. In the 2020 fishing year, 73% of the scallop harvest was taken in the months from December 2019 to January 2020 (the fishery was closed in November 2019). In the 2021 fishing year, 87% of the scallop harvest was taken in November and December 2020.

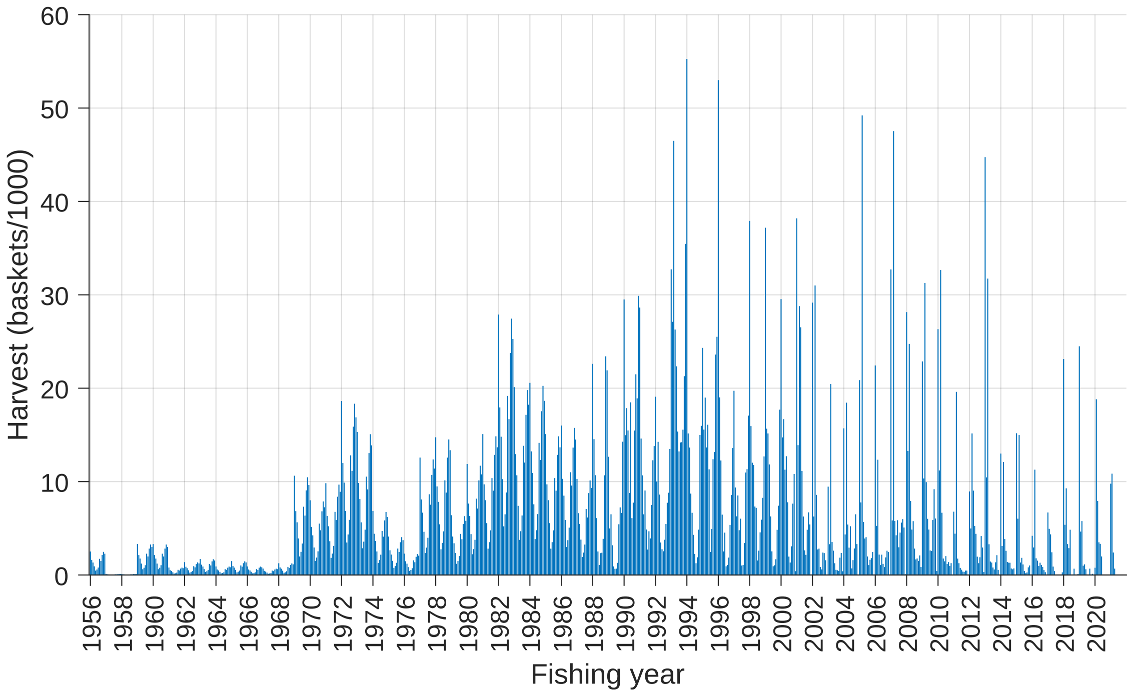

Figure 3.2: Monthly estimated saucer scallop harvest 1956–2021

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Harvest input data for the model was the number of baskets by fishing month and fishing year (Figure 3.2). The graph in Figure 3.1 applied a conversion formula (Table 2.2) to summarise the harvest by meat weight by fishing year.

3.1.2 Standardised catch rates

Abundance measures of standardised catch rates of legal sized scallop for region 3 and region 4 combined were on average 5 baskets per boat day for November 2020–January 2021 and went up to 17 baskets per boat day in February 2021. (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.

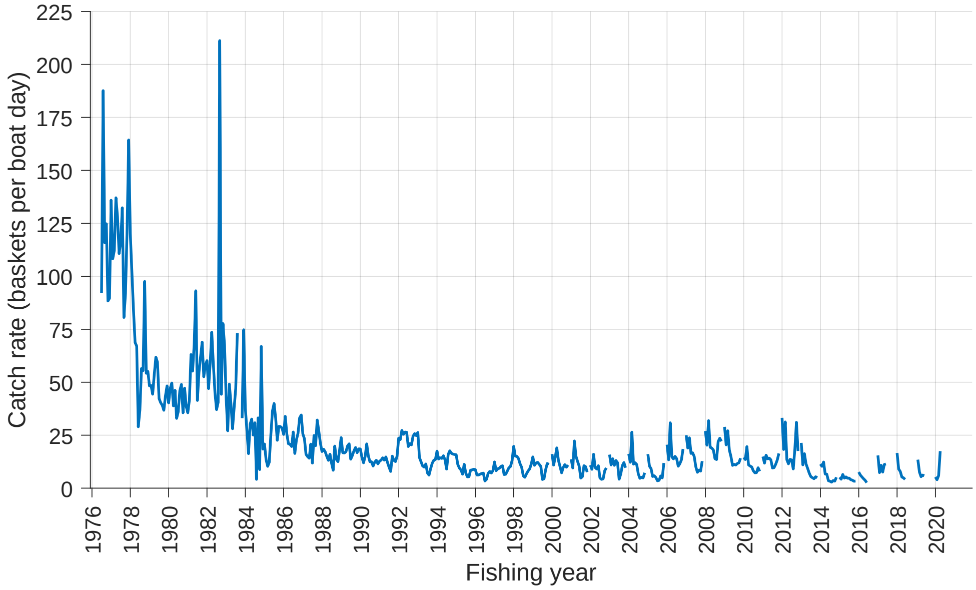

Figure 3.3: Standardised monthly catch rates 1977–2021

3.1.3 Survey estimates

Scallop density (number of scallops per hectare) from the October survey increased from 2020 to 2021 for age 0+, age 1+ and legal sized groups (Figure 3.4). For age group 0+ the estimated 2021 density was 19 scallops per hectare (up from 10 in 2020), for age group 1+ the estimated 2021 density was 56 scallops per hectare (up from 21 in 2020) and for legal sized group the estimated 2021 density was 45 scallops per hectare (up from 15 in 2020).

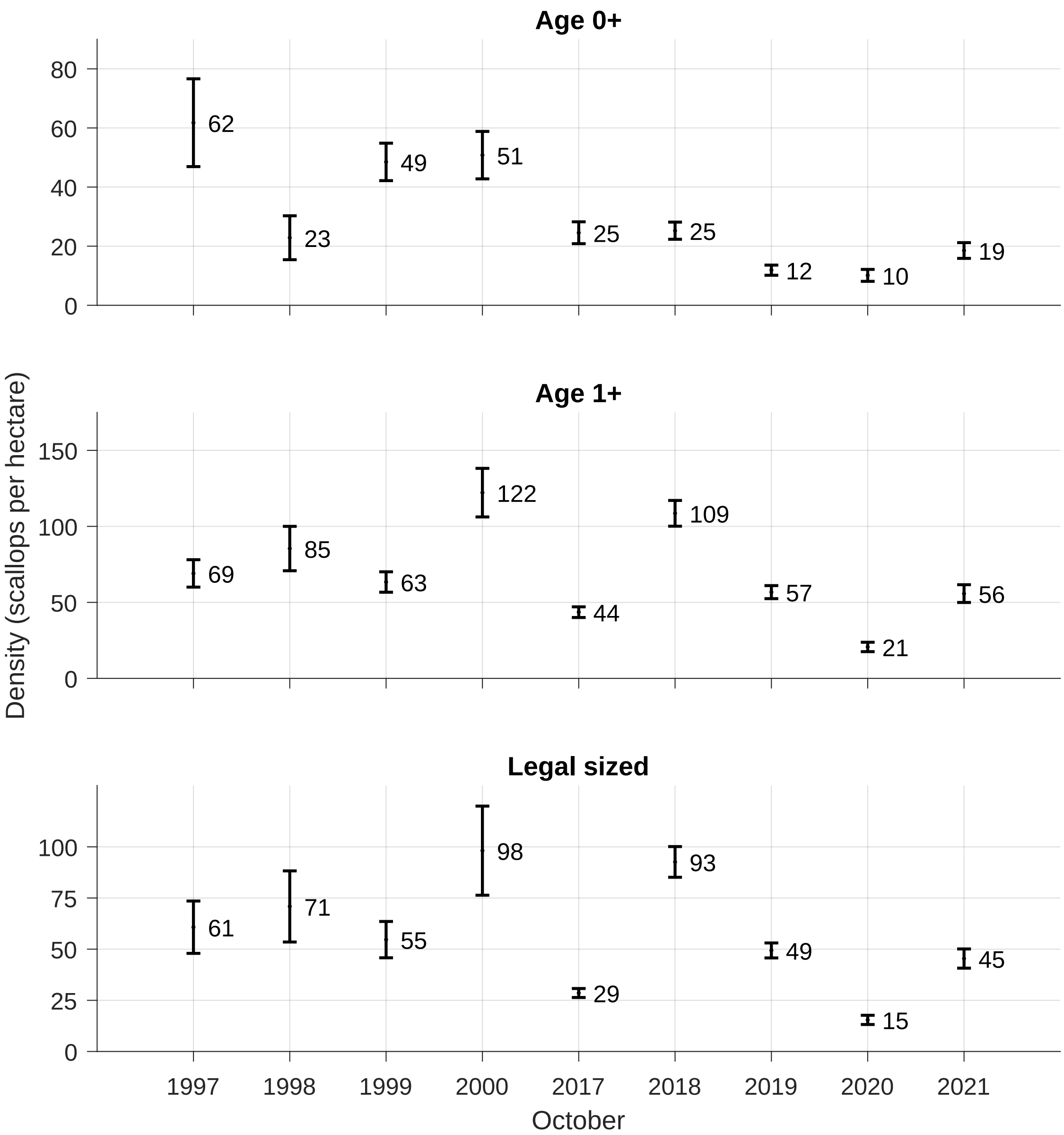

Figure 3.4: Annual mean modelled densities per hectare by year for age 0+, 1+ and legal sized scallops

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 C.5

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

Parameter	Estimated value (s.e.)
Virgin recruitment R_0	2.418×10^9 (0.188×10^9)
Steepness h	0.23 (0.0054)
Amplitude of seasonality a	0.317 (0.034)
Closure effect on January q_{Jan}	0.251 (0.0695)
Von Mises mode of monthly recruitment θ	1.974 (0.305)
Von Mises variance of monthly recruitment κ	1.105 (0.195)

3.2.2 Biomass

The estimated 2021 spawning biomass was 15% of unfished levels with 95% confidence interval of 10–29% (Figure 3.5). The fish down of the biomass in the early years was minimal (in 1970 the estimated spawning biomass was at 90% of unfished spawning biomass in 1956).

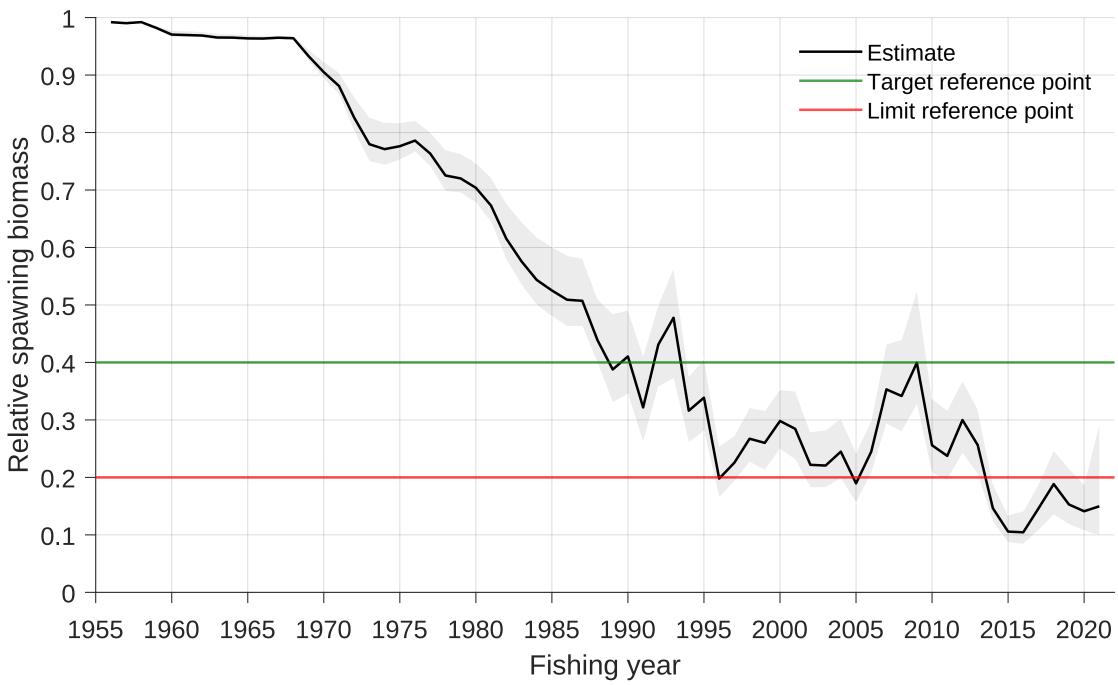

Figure 3.5: Annual spawning biomass ratio (± 95% CI) 1956–2021

Relative spawning biomass for the sensitivity scenario (region 3 only) was estimated at 9% in 2021 (Figure 3.6). Additional information for this scenario includes catch rates, catch rate fit, survey density fit, parameter estimates and MCMC diagnostics (Appendix C).

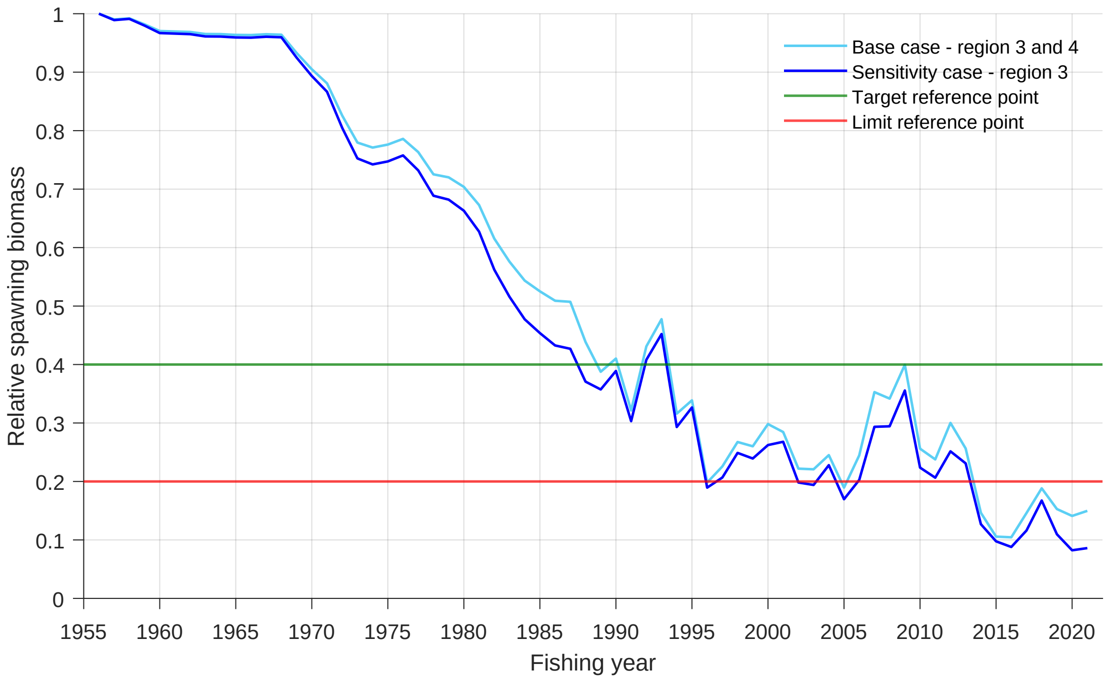

Figure 3.6: Estimated spawning biomass trajectory relative to virgin for saucer scallop, 1956–2021, for the sensitivity run (as described in Section 2.6.5)

3.2.3 Harvest targets

The equilibrium harvest informs on the productivity of the stock at different spawning biomass levels (Figure 3.7). Maximum sustainable yield occurs at spawning biomass of 44% of unfished levels and equilibrium harvest at current (15%) biomass levels is 234 t (Table 3.2). The potential maximum sustainable yield at 44% biomass is 366 t per year, with effort of 115 711 effort units.

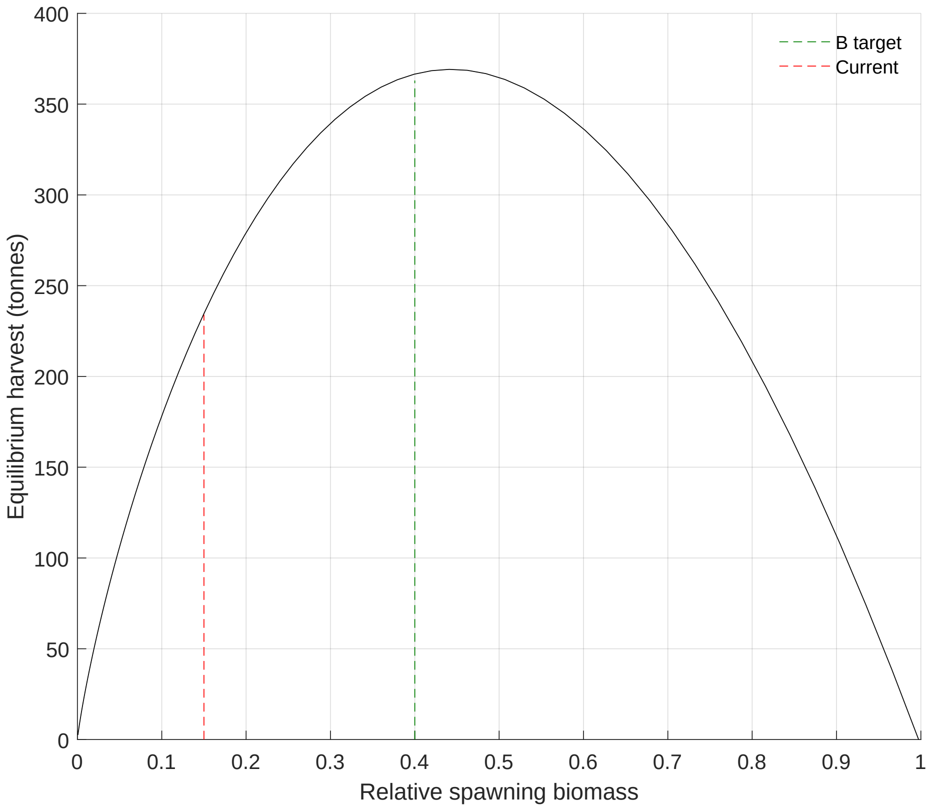

Figure 3.7: Equilibrium harvest curve for saucer scallop

Table 3.2: Current and target indicators

Indicator	Estimate
Current (2021) spawning biomass (relative to unfished)	15% (10–29%)
Spawning biomass at maximum sustainable harvest	44%
Current (2021) harvest	161 t
Sustainable harvest at spawning $B_{40\%}$	363 t (303–432 t)
Maximum sustainable harvest	366 t
Equilibrium harvest at current biomass	234 t

The forward projection scenarios are shown in Figure 3.8. With fishing effort of 275 000 effort units (or 5000 boat-days), the spawning stock did not recover. The projections estimated that with fishing effort of 80 000 eu, spawning biomass did not reach levels of 40% unfished spawning biomass by 2040. Under zero fishing effort, i.e. no fishing, the spawning stock rebuilt to levels of 40% unfished spawning biomass in 10 years.

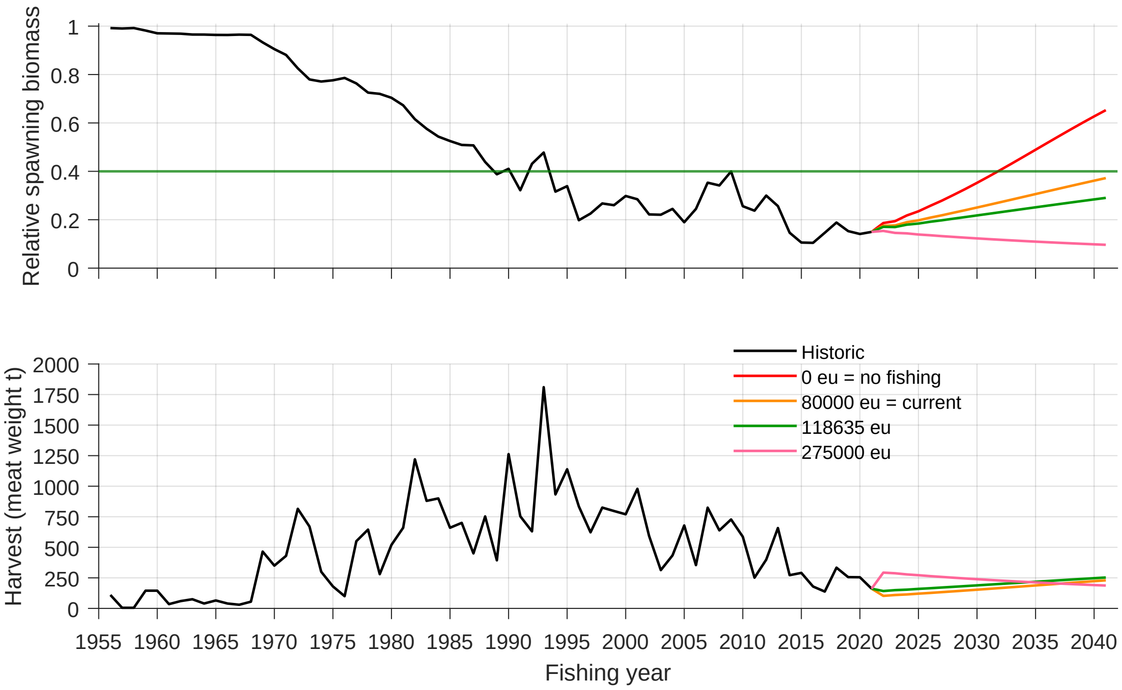

Figure 3.8: Forecasts of annual spawning biomass and harvest

4 Discussion

4.1 Stock status

Spawning stock biomass was estimated at 15% of unfished levels in 2021 for the base case and 9% of unfished levels when considering region 3 alone. The 2021 harvest of 161 t is below the 234 t that represents equilibrium harvest at 15% biomass.

4.2 Performance of the population model

There was model convergence (maximum likelihood estimates), and satisfactory goodness of fit to the trends in data. 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 and estimates of steepness and virgin recruitment were highly correlated.

One limitation of the model is that it is non-spatial and therefore unable to represent partial or asymmetric connectivity between the aggregations. Oceanographic modelling suggests that the scallop aggregations off K'gari and further south may be unable to contribute recruits back to the rest of the stock (Courtney et al. 2015; O'Neill et al. 2020). The precise impact of this is unclear without an explicitly spatial model, however it does suggest that the confidence intervals should be treated as underestimates.

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 annual fishery independent abundance surveys to validate stock status and to optimise management procedures need to continue. 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

A rebuilding strategy is required and the results of this assessment should be used to inform its development.

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.

Future assessments might be improved by considering the spatial variation in natural mortality detected in the study, and possible seasonal variation. *Ylistrum balloti* has a relatively narrow temperature tolerance and results from the study in Courtney et al. (2020) indicated that M was higher over summer. Although speculative, the increase in M over the last 40 years may be related to the increase in winter sea surface temperature (SST) in the fishery over this period (O'Neill et al. 2020). If M increases with SST then it may affect the target reference points used for managing fishing effort and potential yields (Wortmann et al. 2020).

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

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).

As discussed in Section 4.2, a limitation of the current model is that it is non-spatial. There is evidence the aggregations are not globally connected and future work should reconsider the case for some level of spatial structure.

4.5 Conclusions

This assessment was commissioned to establish the stock status of saucer scallop on Queensland's east coast and inform the Sustainable Fisheries Strategy. The base case model scenario suggested spawning biomass is currently around 15% of unfished levels. Some recommendations for management, monitoring and the next assessment have been made.

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Appendix A Model inputs

A.1 Harvest from trawl regions

Harvest from the southern offshore region was associated with irregular and infrequent scallop catches. In 2020 and 2021 fishing years more than half the total saucer scallop harvest came from the southern offshore region in (162 and 130 tonnes (meat weight) respectively) (Figure A.1).

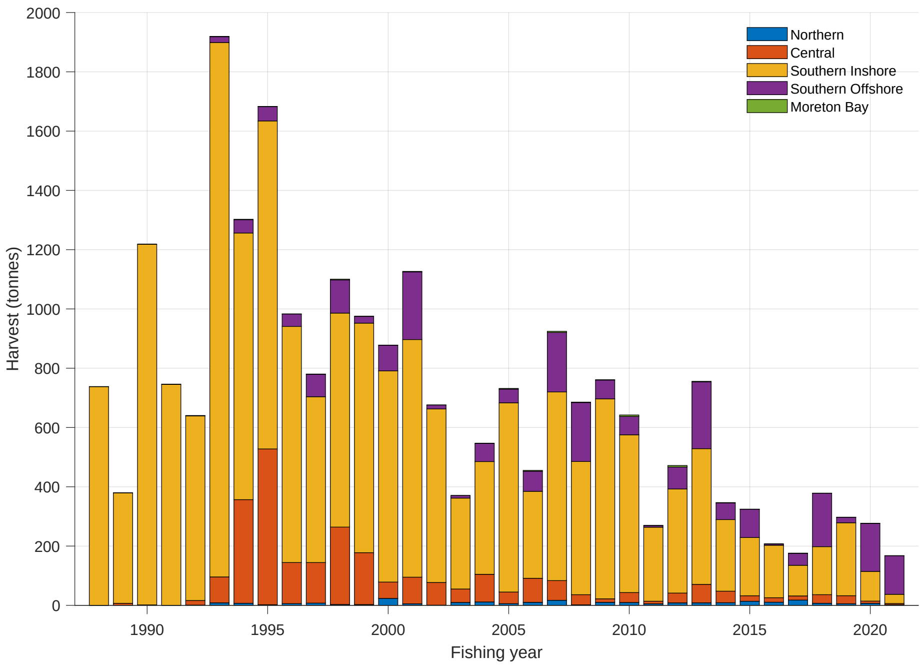

Figure A.1: Annual estimated saucer scallop harvest 1988–2021 from trawl regions

A.2 Data filters for catch rate standardisation

The following filters were applied to the CFISH logbook data to get the data set for catch rates:

- Baskets > 0
- FishingMethodType is trawl (99.9% of records were trawl) or trawl beam (0.1% records were trawl beam)
- CaabSpeciesID in (23270001,23270000) (Scallop - unspecified , Scallop – saucer) (95% of CFISH logbook records of total scallop harvest were in these categories). For harvest data the CaabSpeciesID of 23270003 (Scallop - mud) and 23270005 (Scallop – queen) were also included
- Longitude ≥ 142.5
- grid = "V32" Or "T30" Or "S28" Or "S29" Or "U31" Or "T29" Or "T28" Or "U32" Or "S30" Or "V31" Or "T31" Or "U30" Or "W34" Or "W32" or "W33" or "W34" or "W35"(main scallop fishing grounds of Yeppoon, Hervey Bay, Bustard Head, K'gari)
- Net type not equal to Beam
- Hours ≤24

A.3 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 and 2021 stock assessments (Wortmann et al. 2020; Wortmann 2021).

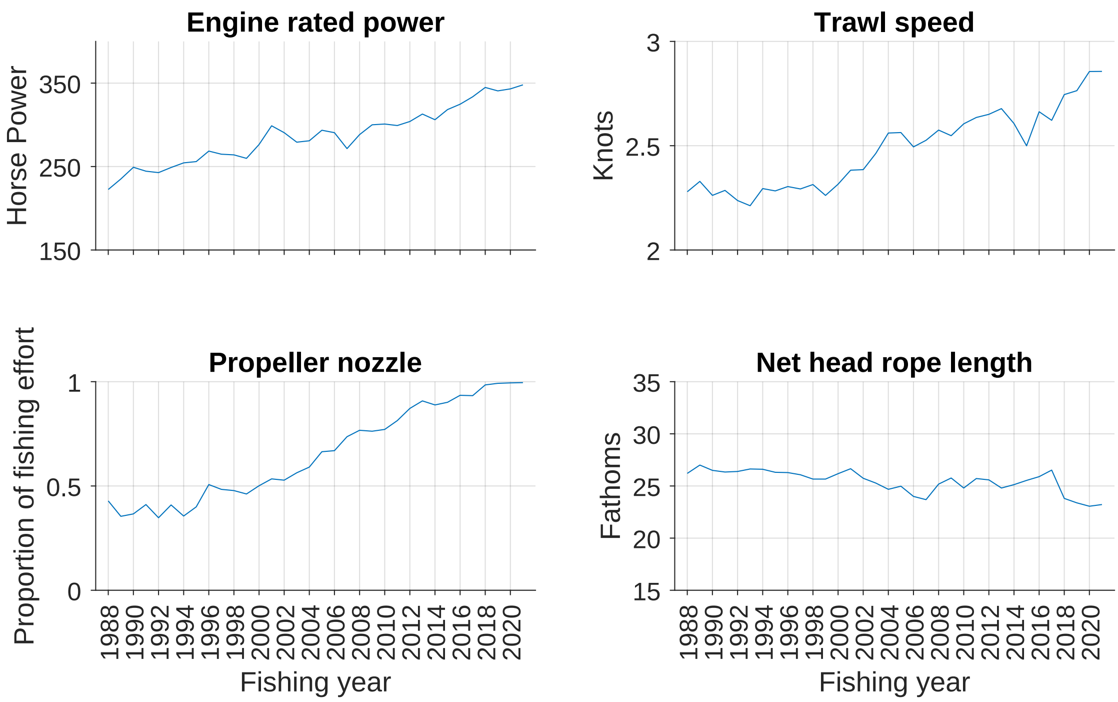

Figure A.2: The fleet average engine rated power, trawling speed, use of propeller nozzles and net size by fishing year—averages were weighted according to the number of days fished by each vessel in each fishing year

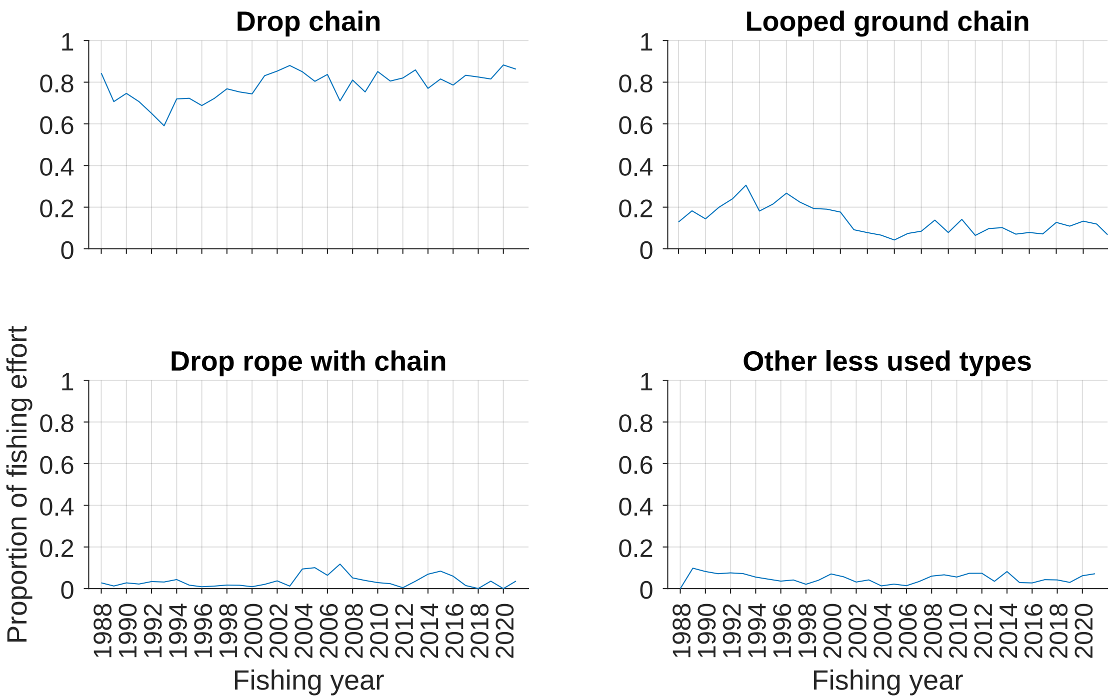

Figure A.3: The proportion of total annual fishing effort by vessels using various ground gear configurations

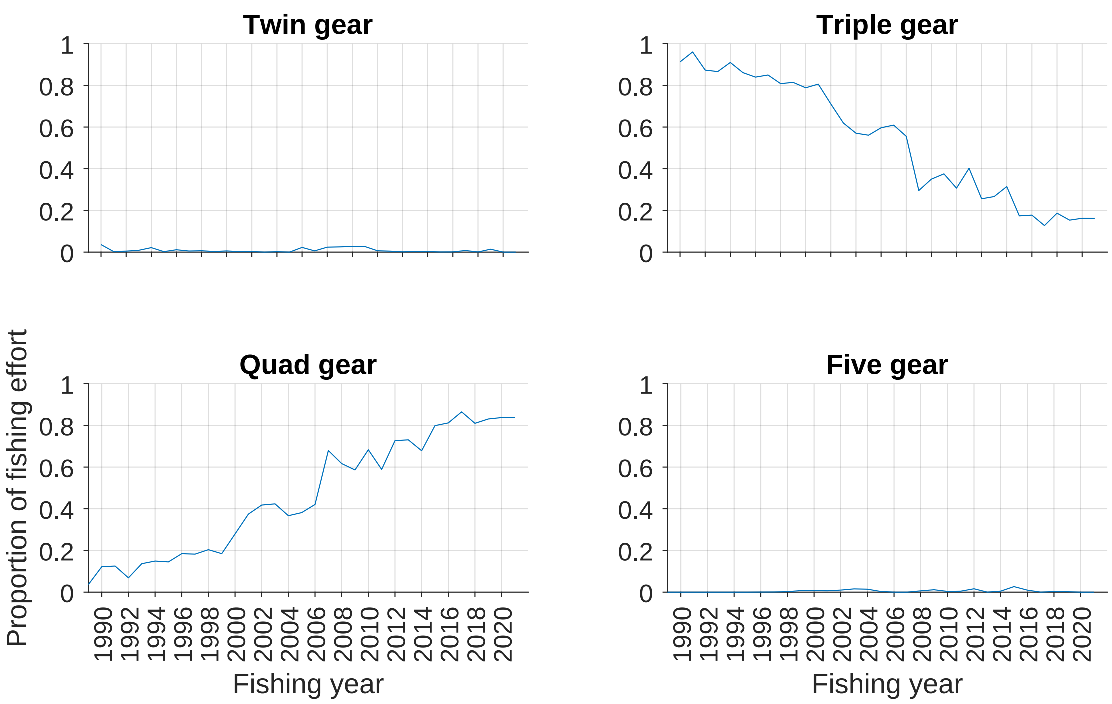

Figure A.4: The proportion of total annual fishing effort by vessels using various net configurations

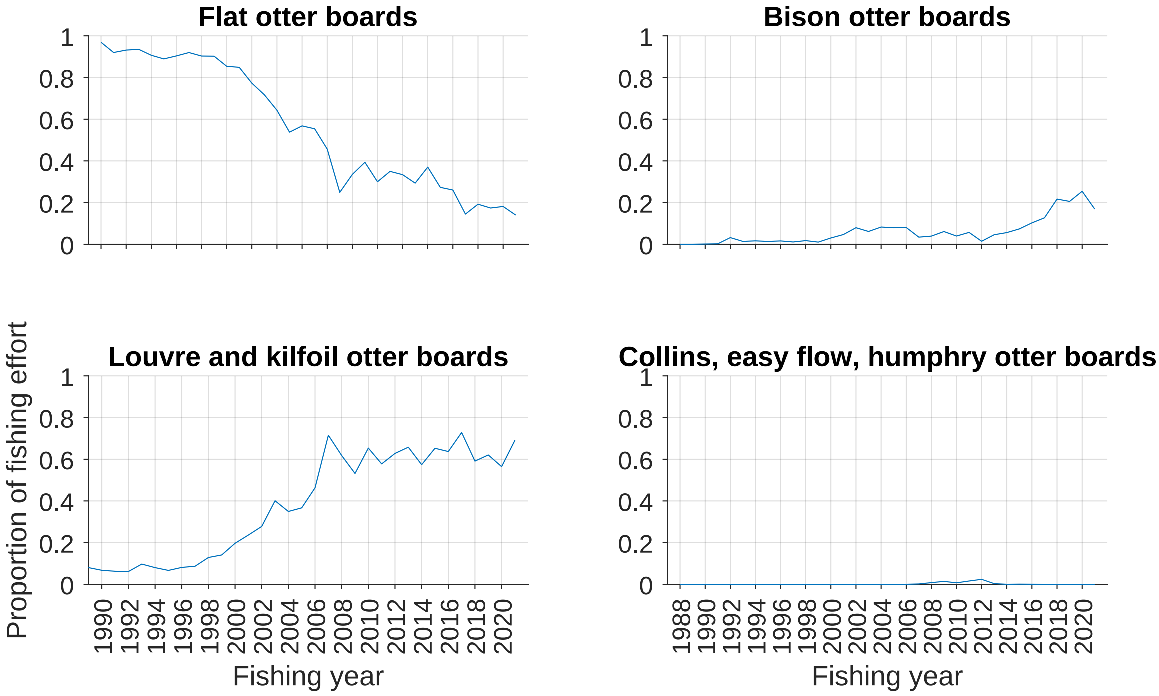

Figure A.5: The proportion of total annual fishing effort by vessels using various otter board configurations

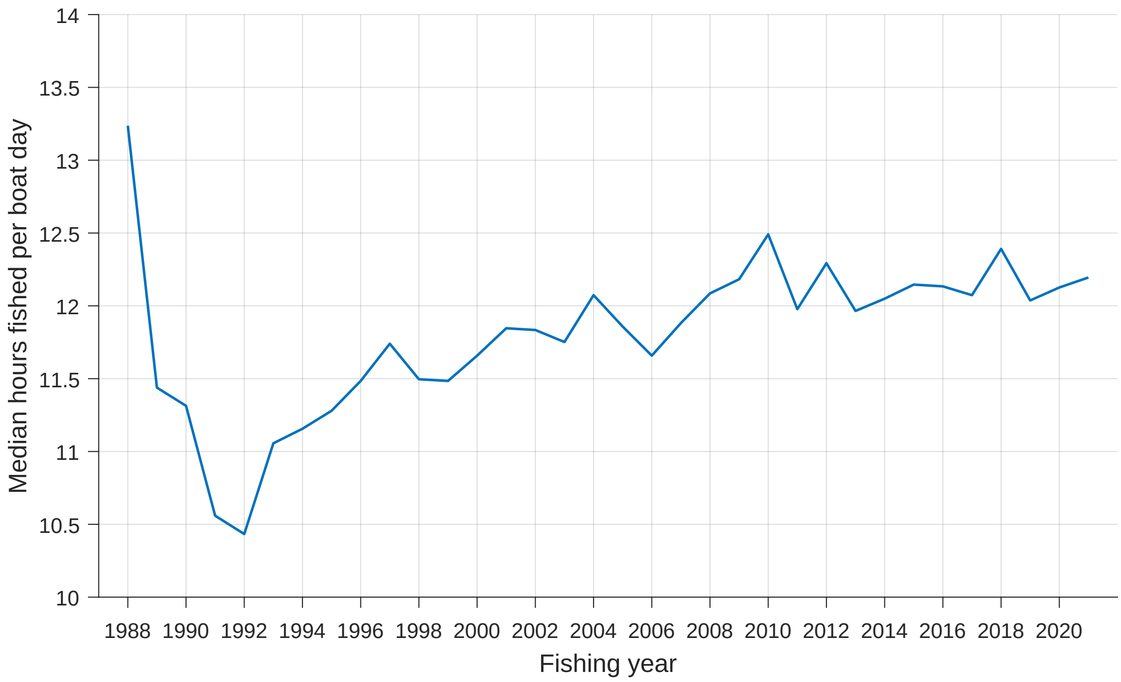

Figure A.6: Median hours fished per boat-day from the linear mixed model data

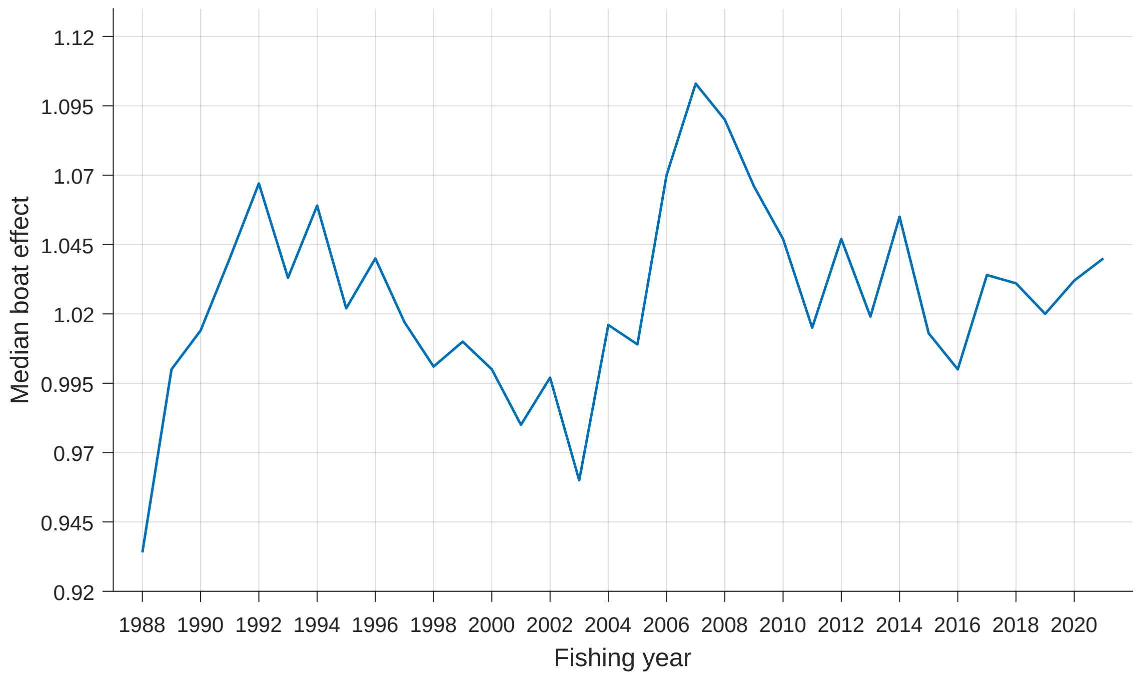

Figure A.7: Median annual boat effect from the linear mixed model data

A.4 Fishing power

The 1988–2021 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.8, where fishing power increased by about 16% from 1989–2021. 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 25% from 1989–2021. The increase in fishing power from 2019–2021 is likely due to worse boats leaving the scallop fishery (Figure A.7).

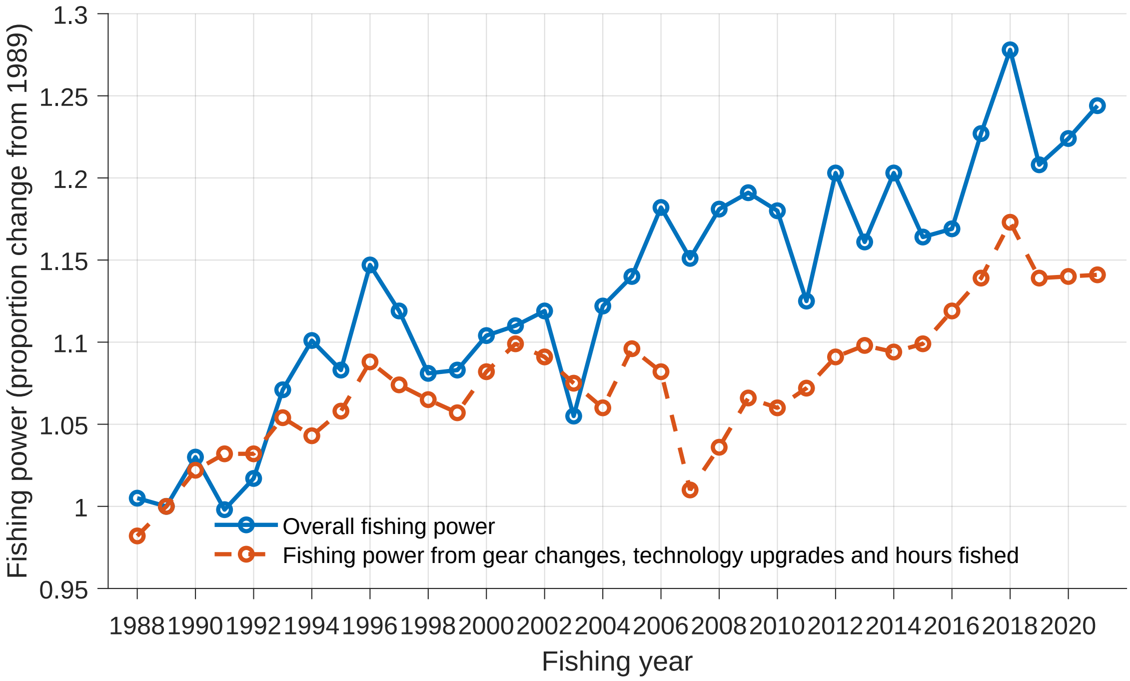

Figure A.8: Annual fleet fishing power on saucer scallops

A.5 Catch rates with target

Historically, Moreton Bay bugs were retained as byproduct of prawn and scallop trawling, but over time their popularity and price have increased and they have become increasingly targeted by fishers. In recent years in the Queensland scallop fishery, the scallop catch has declined and fishers have targeted bugs to such an extent that their catch value now exceeds that of the scallops. For example, in the catch rate data set for saucer scallops, the corresponding nominal bug catch rate (catch divided by effort) for the scallop fishers showed an increase since 2002 (the Caabspecies bug codes were 28821901 (Bugs Balmain), 28821903 (Bugs Moreton Bay) and 28821904 (Bugs unspecified) (Figure A.9).

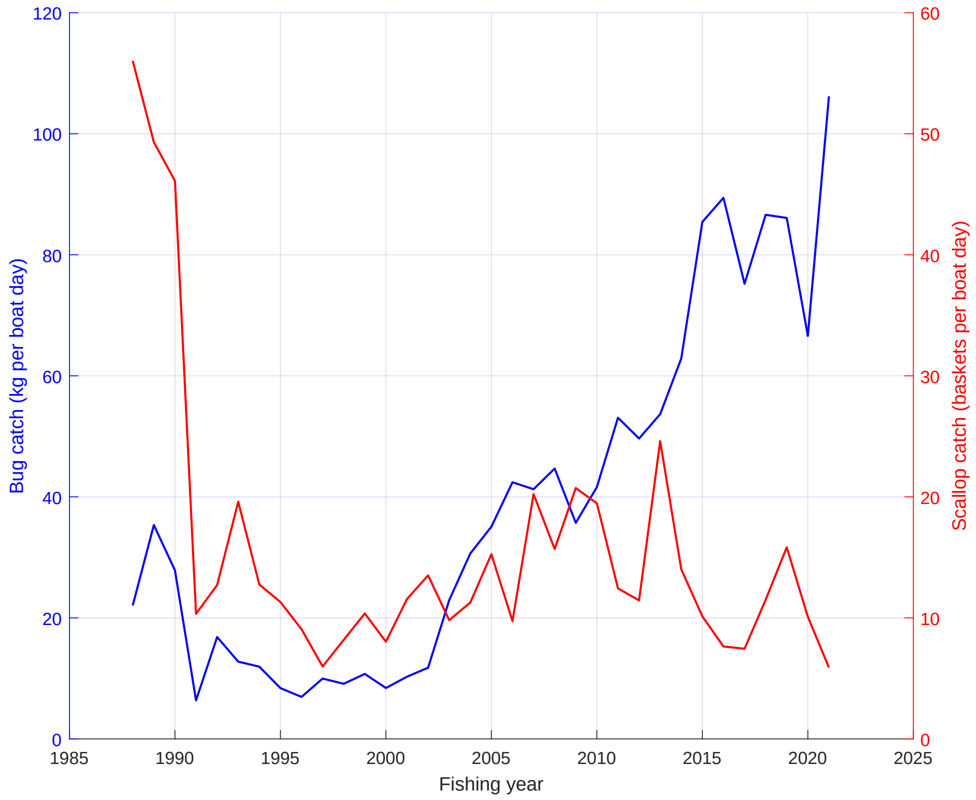

Figure A.9: Nominal catch rate of saucer scallops (red) and bugs (blue) from logbooks 1988–2021 in region 3

Quantifying the fishing effort targeted at bugs and differentiating it from the scallop effort is challenging. This complicates the estimation of reliable catch rate time series that can be used as an index of abundance for each group (i.e. bugs, prawns, scallops). Despite their high value, Queensland has not previously undertaken a stock assessment of Moreton Bay Bugs, beyond yield-per-recruit analyses. This is largely because the Bug catch is composed of two species, reef bugs (*Thenus australiensis*) and mud bugs (*Thenus parindicus*) which are not differentiated by fishers in the logbook data. Mud bugs are the smaller of the two species and generally occur in depths of 10–30 m, while the larger reef bug generally occurs in depths of 30–60 m. Although there is some spatial separation of the species it is not possible to breakdown the catch of each from the logbook data alone.

The methods of Dichmont et al. (2001) were used to develop a guideline to separate when scallops were the target species and when bugs were the target species for the catch rate standardisation in Section 2.4.1. A target species group was defined as:

$$\begin{aligned} &a\ reasonable\ catch\ of\ a\ particular\ species\ group\ for\ a\ particular\ fishing\ year\ was\ defined\ to\ be\ any\ catch \\ &that\ exceeded\ the\ lower\ quartile\ of\ the\ non-zero\ catches\ of\ that\ species\ group\ for\ that\ year \end{aligned} \tag{A.1}$$

Table A.1 gives the quartiles and maximum of the daily fisher logbook catches for bugs (in kg) and saucer scallops (in baskets) for the fishing years 1988–2021. The quartiles were calculcated from the bug catch in all regions and the scallop catch from the main scallop fishing ground region 3. The CAAB species codes for bugs from the logbooks were 28821901 (Bugs Balmain), 28821903 (Bugs Moreton Bay) and

28821904 (Bugs unspecified). Around one third of the total bug catch was caught in the main scallop fishing ground (region 3) (Table A.2). A boxplot of the daily fisher bug catch in Figure A.10 shows most of the daily bug catch was well below 100 kg per fisher day.

Table A.1: Annual quartiles and maximum of the non-zero catches of bugs (in kg) and saucer scallops (in baskets)

	Bugs				**Scallop**			
Fish year	25%	50%	75%	Max	25%	50%	75%	Max
1988	4	8	18	804	16.75	38.5	67.5	200
1989	3	9	20	910	23	45	70.5	186
1990	4	9	20	652	3	8	40	300
1991	3	7	15	740	1.8125	5	11	40
1992	3	9	20	1320	4	9	14	280
1993	3	10	20	1500	6	15	24	300
1994	4	10	20	765	5	9.5	15	275
1995	4	10	20	600	6	10	13	330
1996	3	10	20	450	4	7	11	330
1997	3	9	20	680	3	5	7.5	150
1998	3	8	20	300	4	7	10.5	80
1999	3	7	17	930	4	8	13	140
2000	2	5	13	740	4	6.5	10	258
2001	2	5	14	1050	5	8.5	13.875	225
2002	2	5	20	570	5	9	16	300
2003	2	5	20	805	3	7.75	12	145
2004	2	5	20	440	5	10	15	95
2005	2	5	20	600	4.3125	9	15	430
2006	2	6	30	480	3	6.5	12	120
2007	2	10	35	500	6	13	25	260
2008	2	6	30	315	5	11	20	161
2009	2	8	30	1100	10	16	25	167
2010	2	8	35	420	8	15	25	495
2011	2	5	30	290	4	9	16	343
2012	2	8	40	400	5.5	10	15	180
2013	2	8	40	300	7.75	16	32	210
2014	2	7	40	450	3	8.5	20	150
2015	2	7	40	1200	2	5	14	120
2016	2	6	43	1000	2	3	7	612
2017	2	5	50	760	2	4	8	275
2018	2	5	60	640	3	7	13	210
2019	2	6	60	1515	3	8	19	350
2020	2	10	60	850	2	6	11	180
2021	5	20	70	486	1.5	3	6	120

Table A.2: Bug catch from logbooks 1988–2021

Caab species ID	Caab species common name	Catch region 3 (t)	Catch all regions (t)	Percentage catch from region 3
28821901	Bugs Balmain	553	1799	31%
28821903	Bugs moreton bay	6,209	16738	37%
28821904	Bugs unspecified	83	310	27%

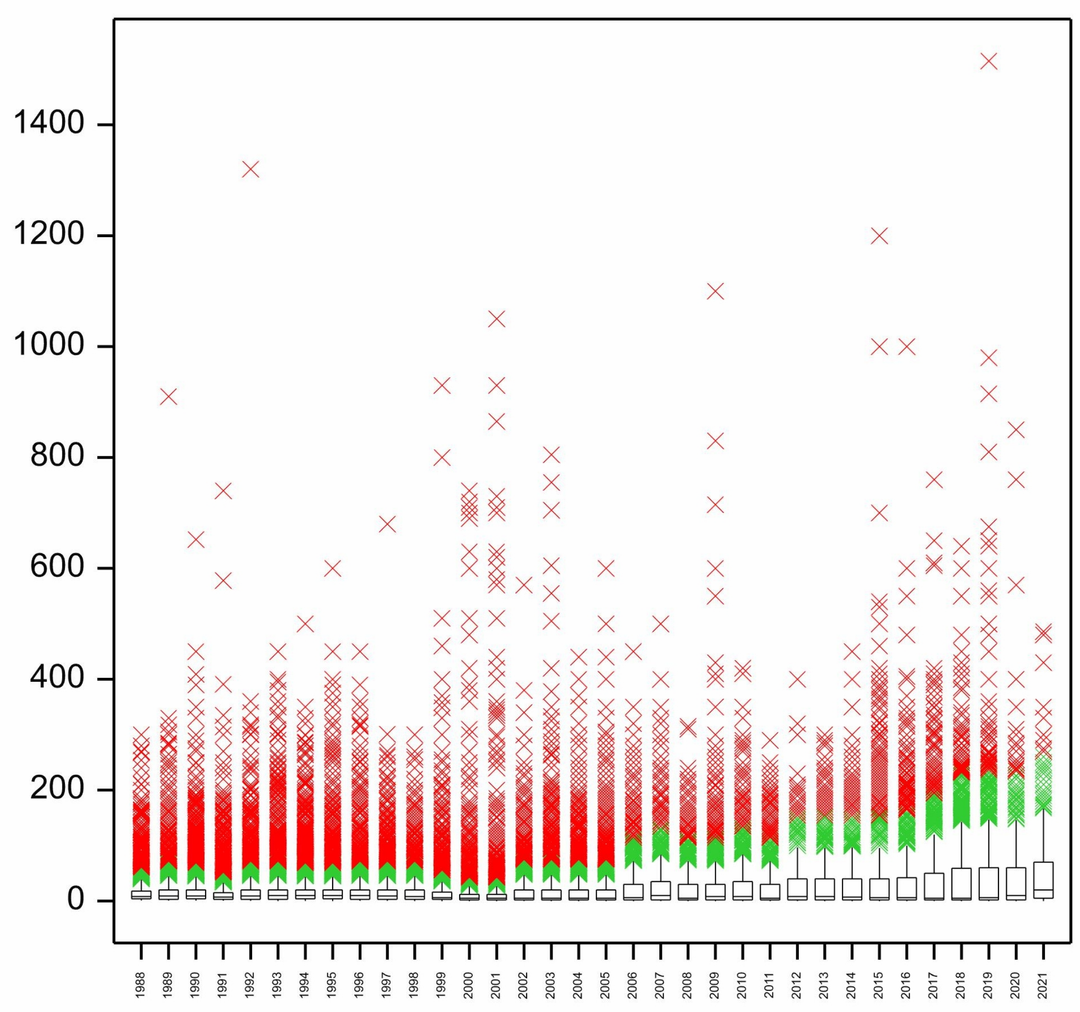

Figure A.10: Boxplot of daily fisher bug catch 1988–2021

A predictive binomial model relating to the probability of reasonable catch for each species group was developed. The analyses used daily logbook information per vessel operation for region 3. The model was programmed in Genstat (VSN International 2021). The probability of achieving a reasonable catch for either main species group was:

$$log(p/(1-p)) = grid + log(hours\ per\ boat\ day) + lunar + lunar\ adv + grid.c12 + grid.cs12 + grid.c3 + grid.cs3 + grid.c6 + grid.cs6 + grid.c4 + grid.cs4 \quad (A.2)$$

where

- *p = 1* if reasonable catch and 0 otherwise (from equation A.1)

- *lunar* = sinusoidal luminance (lunar) pattern as described by O'Neill et al. (2014)
- *lunar adv* = advanced luminance measure seven days (1/4 lunar period) (O'Neill et al. 2014)
- *grid* = 30 x 30 minute logbook grid
- *c3,cs3,c6,cs6,c4,cs4,c12,cs12* = terms to identify the seasonal patterns corresponding to autumn, winter, spring and summer periods (Marriott et al. 2013)

Let p_B and p_S denote the estimate of the probability of achieving a reasonable catch in bugs and scallops respectively from the model A.2. Results showed there was no tendency for the estimated probabilities to lie close to the horizontal or vertical axes (Figure A.11), thus it was not possible to define a target rule as:

$$\text{if } p_S > p_B \text{ the target is scallops, otherwise bugs} \qquad \text{(A.3)}$$

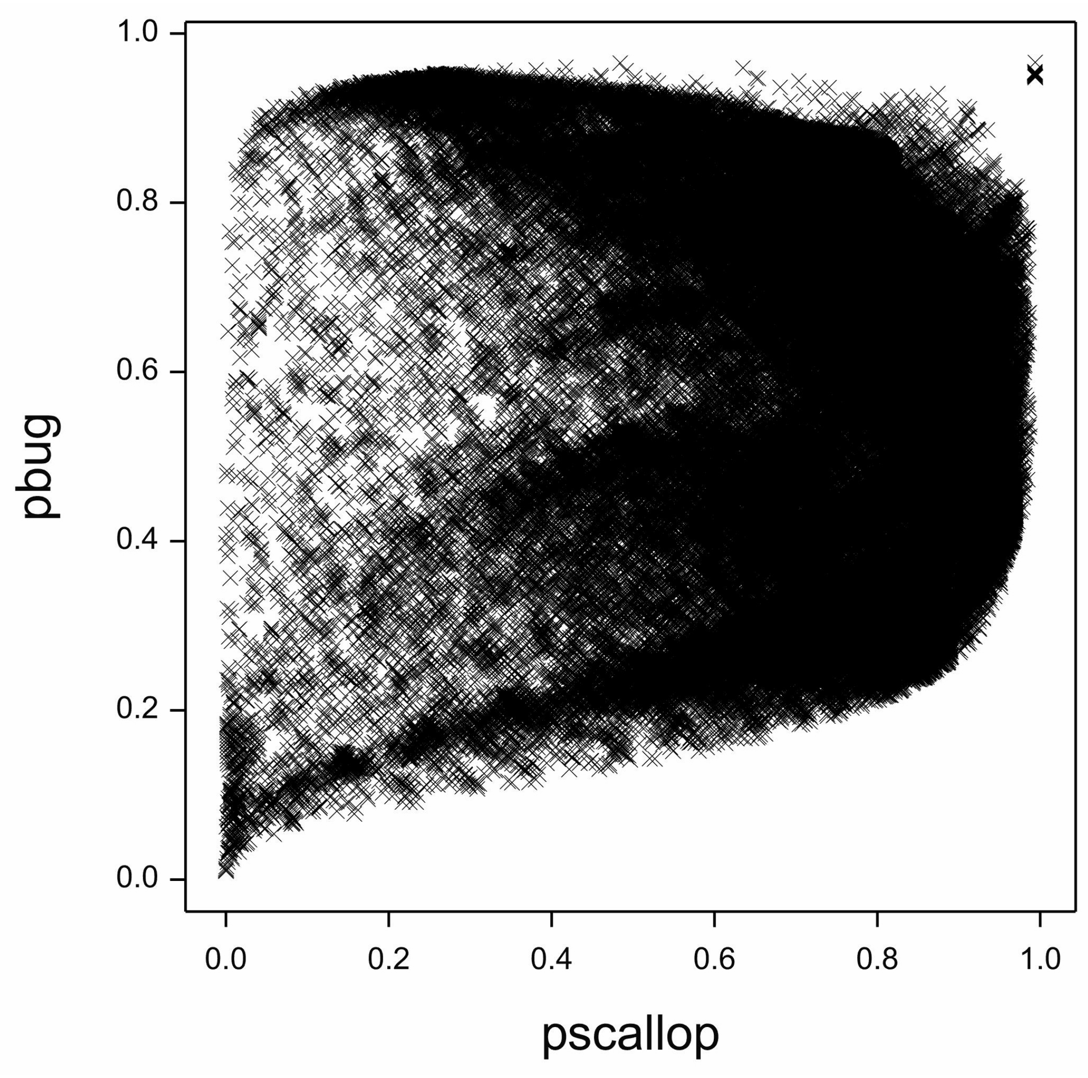

Figure A.11: Estimated probabilities of a reasonable catch of the scallop group verses the bug group

The estimated probabilities were added to the catch rate data and a new factor called target was determined as:

$$target = 1 \; if \; p_S > p_B \; and \; 0 \; otherwise \qquad \text{(A.4)}$$

where

- p_S is the estimate of the probability of achieving a reasonable catch in scallops from A.2
- p_B is the estimate of the probability of achieving a reasonable catch in bugs from A.2

Catch rates were standardised for 1988–2021 using equation (2.1) with the addition of the target factor from A.4:

$$\begin{aligned} log(baskets\ per\ boat\ day) = fishing\ year \times fishing\ month \times area + log(hours\ per\ boat\ day) + log(hp) + \\ log(speed) + sonar + gps + nettype + ggear + target + random(boat\ label\ code) \end{aligned} \tag{A.5}$$

Catch rates were standardized for 1977–2021 using equations (2.2)–(2.4) where equation 2.2 is now written as:

$$\begin{aligned} offsetlog = log(hp) * 0.3647 + sonar * 0.1458 + gps * 0.03268 + (nettype.eq.3) * 0.3826 + \\ (nettype.eq.4) * 0.3250 + (nettype.eq.5) * 0.248179 + (ggear.eq.3) * 0.040714 + \\ (ggear.eq.4) * -0.0779 + (ggear.eq.5) * -0.18653 + target * 0.34275 \end{aligned} \tag{A.6}$$

Catch rates for 1977–2021 were standardised to the same settings as in Section 2.4.1 with the addition of target = 1 (targeting saucer scallops). Fishing year by month trend for January 1977 to October 2021 was the same as the trend predicted by catch rates without a target factor (Section 3.1.2).

Two additional definitions of a reasonable catch were applied to the bug group:

$$\begin{aligned} a\ reasonable\ catch\ for\ a\ particular\ fishing\ year = any\ catch\ that\ exceeded\ the\ third\ quartile\ of\ the \\ non-zero\ catches\ of\ that\ species\ group\ for\ that\ year \end{aligned} \tag{A.7}$$

$$a\ reasonable\ catch\ for\ a\ particular\ fishing\ year = any\ catch\ that\ exceeded\ 100\ kg\ for\ that\ year \tag{A.8}$$

The estimated probabilities from equation A.2 using the rules for bug catch from the definitions (A.7) and (A.8) did not lie close to the horizontal or vertical axes (Figure A.12 and A.13). In the catch rate standardisation in (A.4) and (A.5) the model term ”target” was not significant for these scenarios.

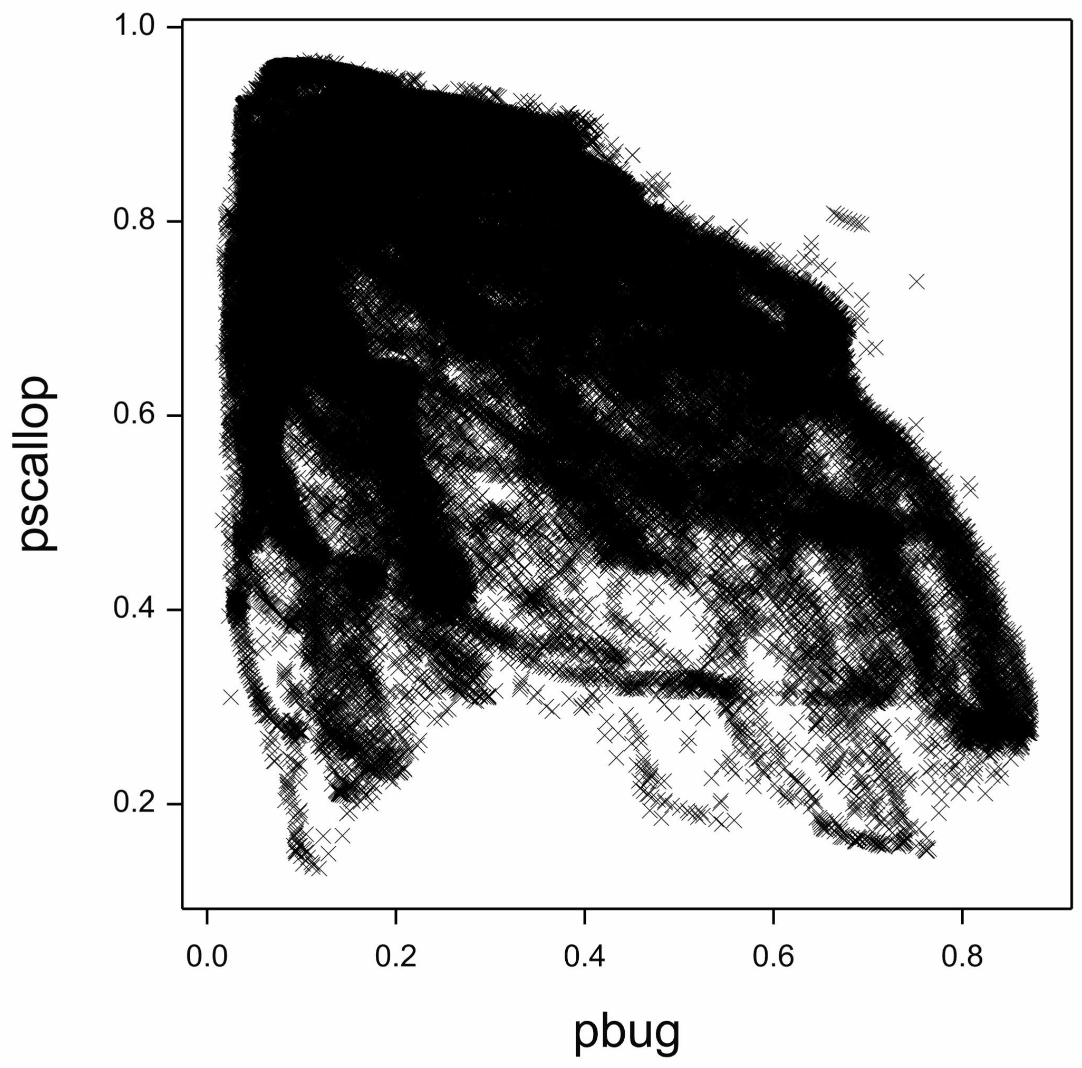

Figure A.12: Estimated probabilities of a reasonable catch of the scallop group verses the bug group where reasonable bug catch defined by (A.7)

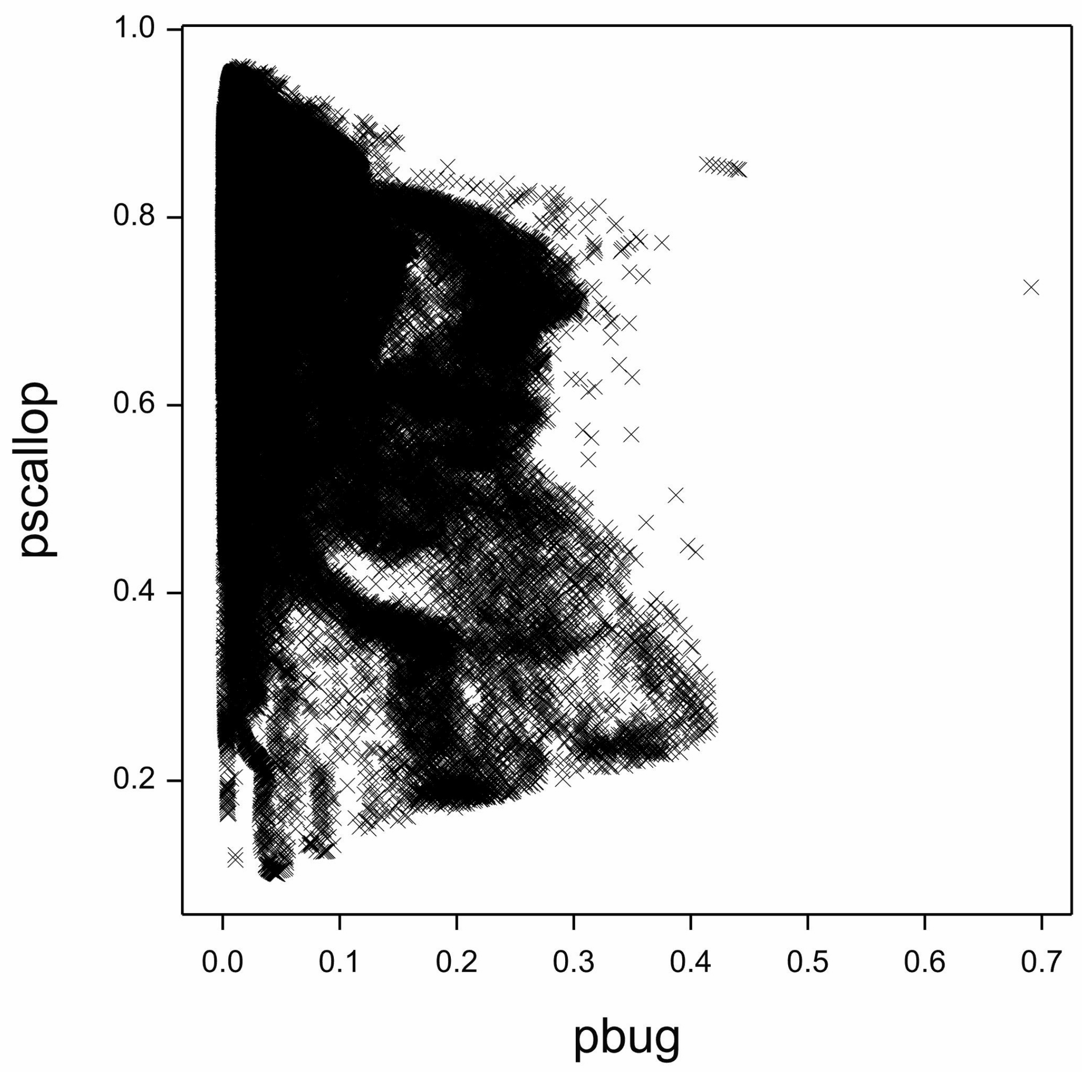

Figure A.13: Estimated probabilities of a reasonable catch of the scallop group verses the bug group where reasonable bug catch defined by (A.8)

Appendix B Model outputs

B.1 Catch rate diagnostics

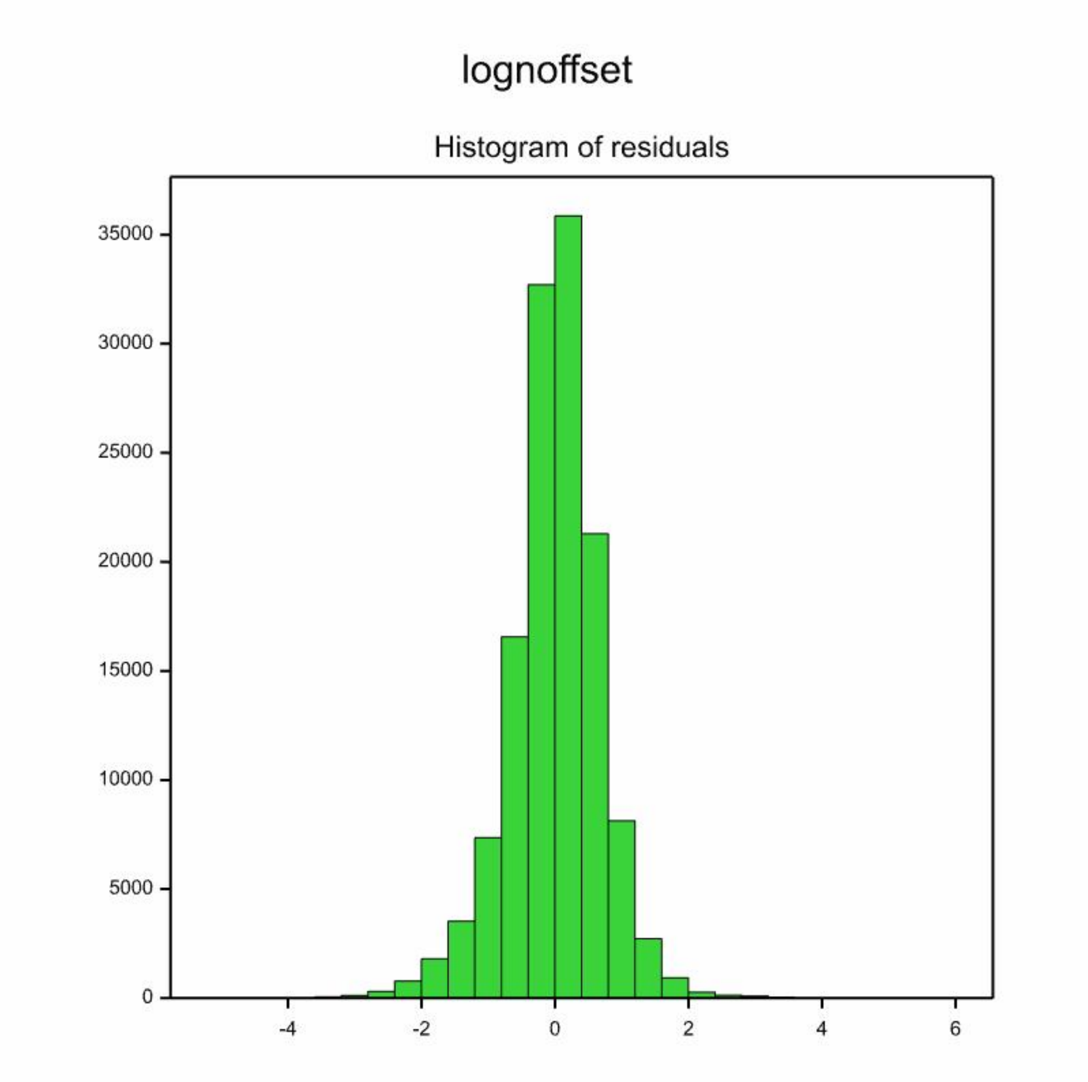

Figure B.1: Residuals for the saucer scallop catch rate analysis 1977–2021

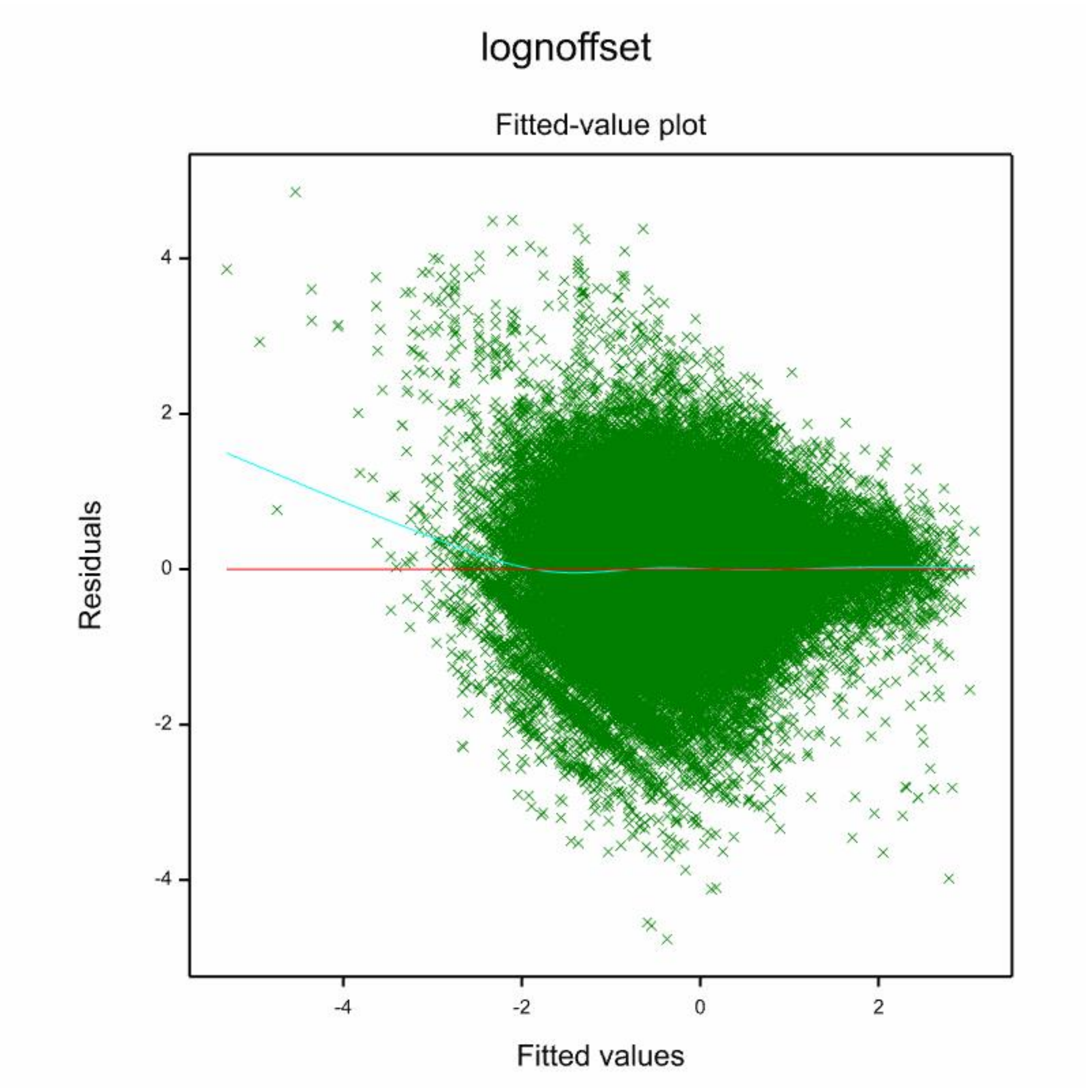

Figure B.2: Fitted values for the saucer scallop catch rate analysis 1977–2021

B.2 Model fit

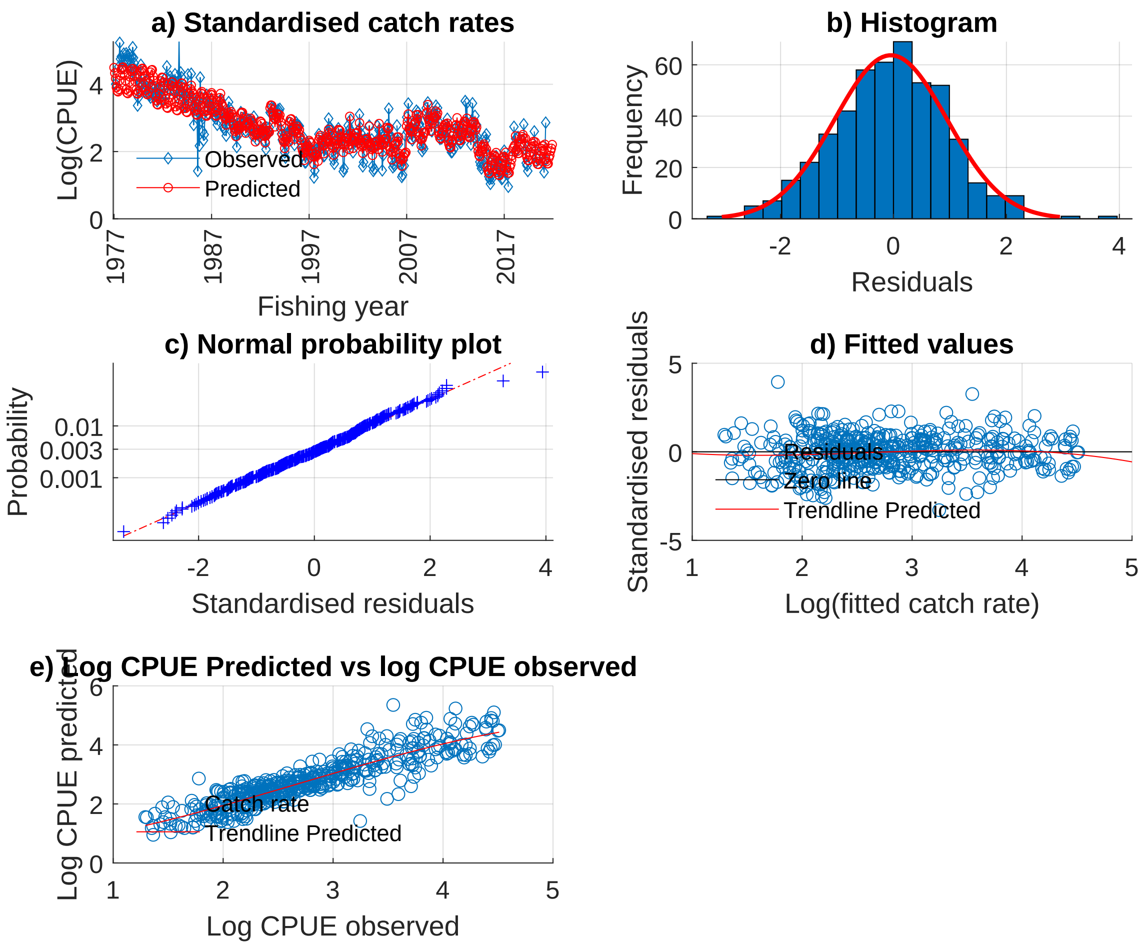

Figure B.3: Catch rate fit-diagnostics

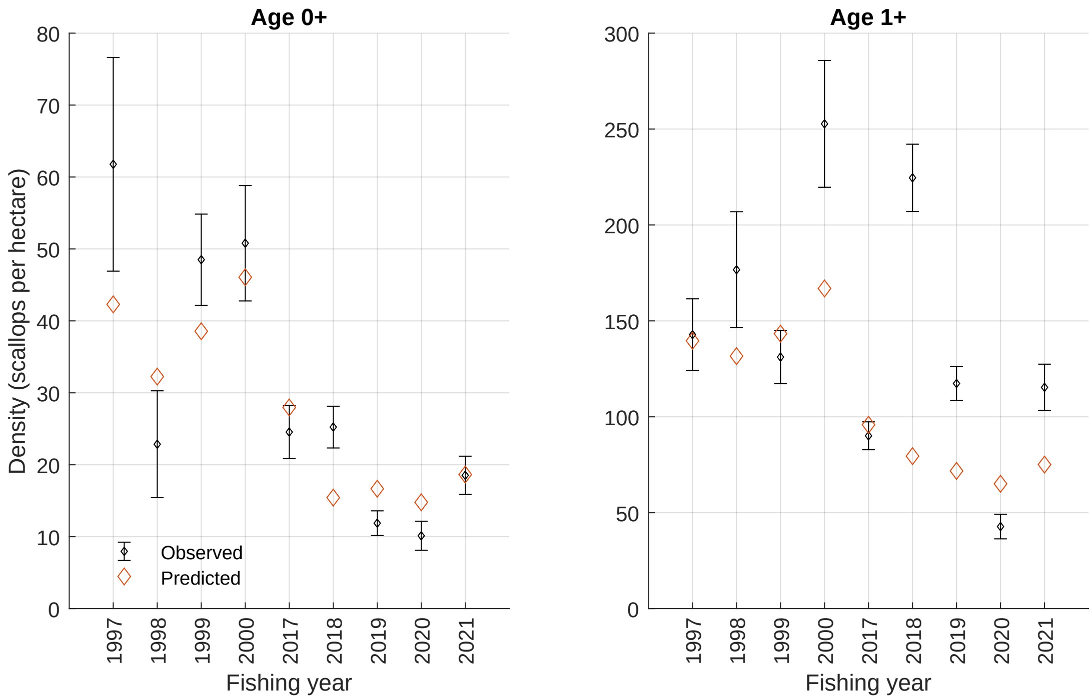

Figure B.4: Age 0+ and 1+ densities from the model (± one standard error)

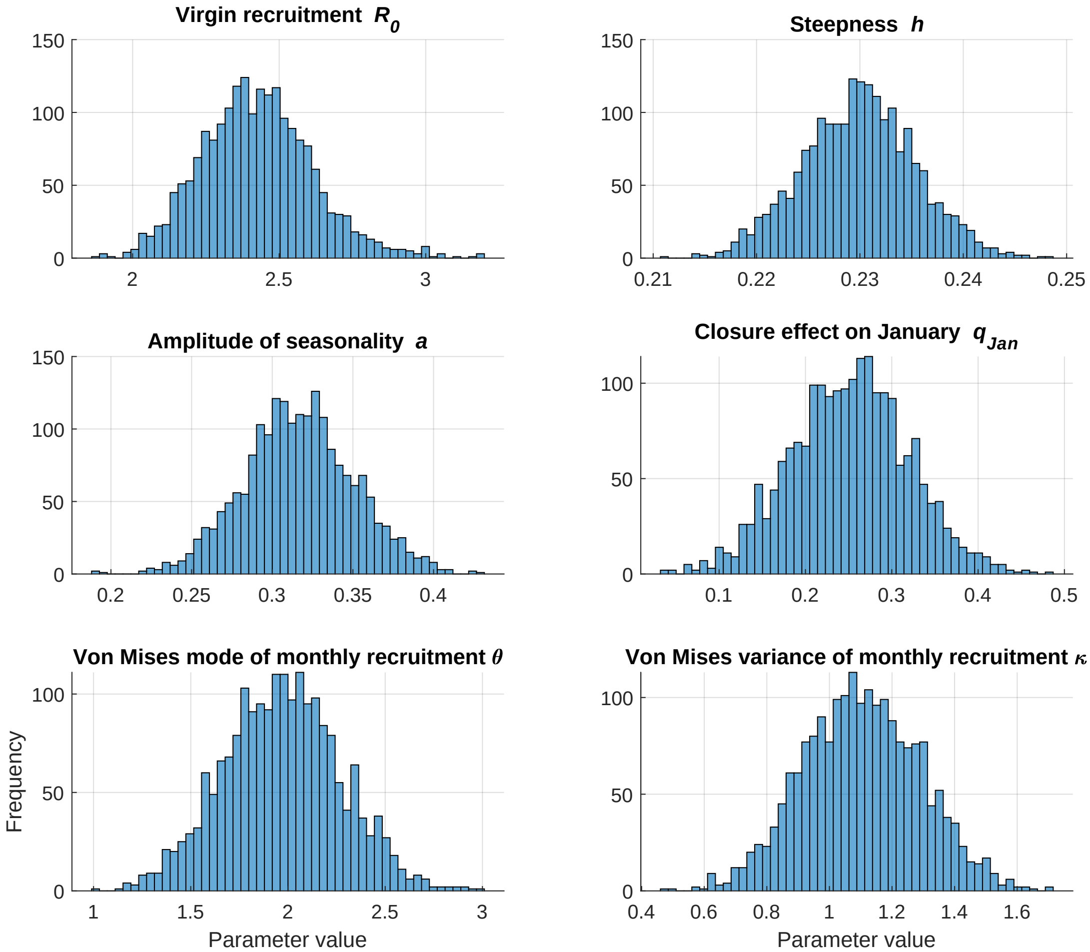

Figure B.5: MCMC parameter estimates for the six main parameters from the model

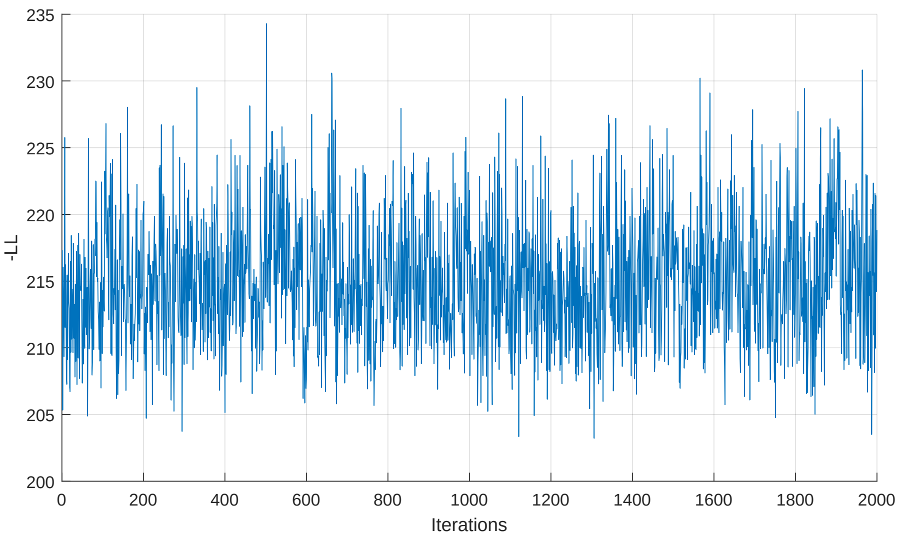

Figure B.6: MCMC –LL trace for the model

Appendix C Sensitivity test: model outputs

C.1 Region 3

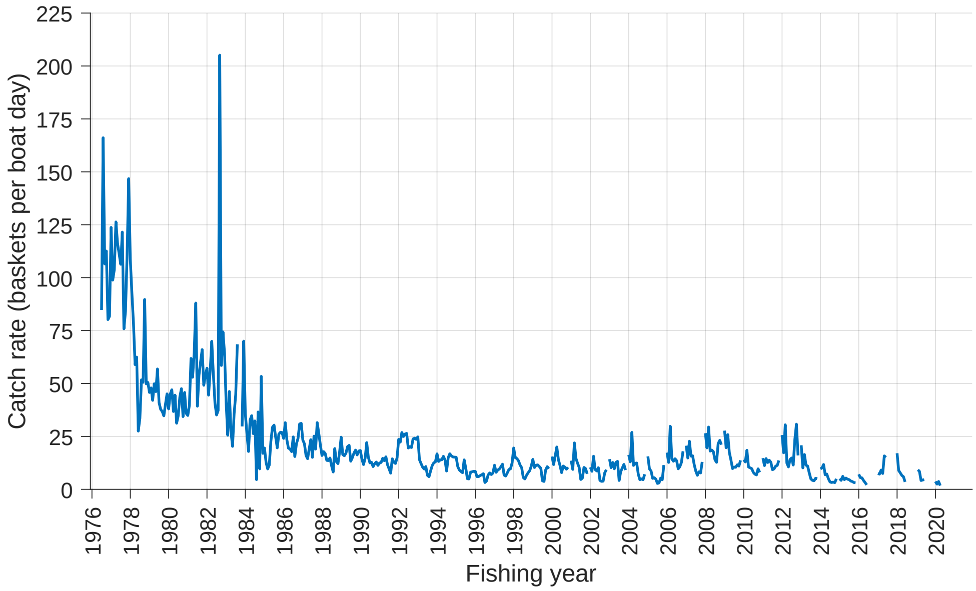

Figure C.1: Standardised monthly catch rates 1977–2021

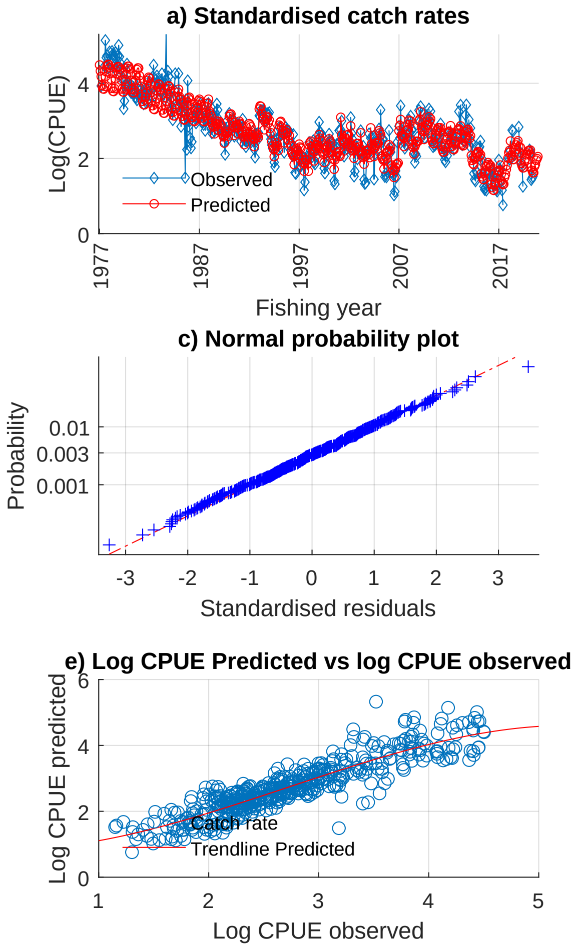

Figure C.2: Catch rate fit-diagnostics

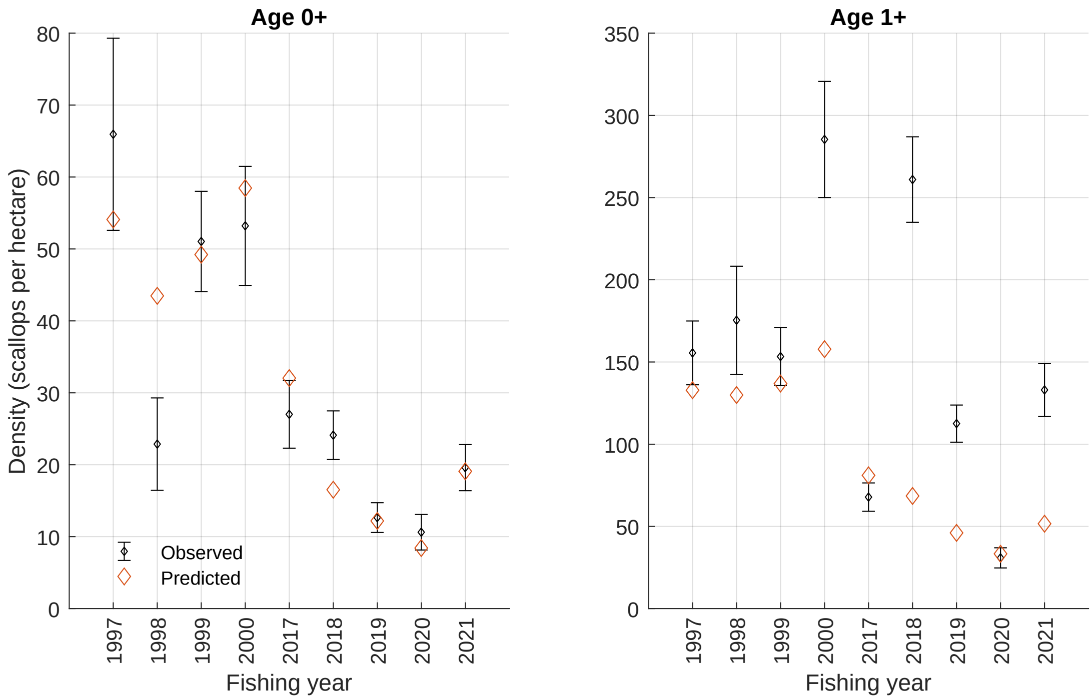

Figure C.3: Age 0+ and 1+ densities from the model (± one standard error)

Table C.1: Parameter estimates for the six main parameters from the median MCMC parameters

Parameter	Estimated value (s.e.)
Virgin recruitment R_0	2.375881×10^9 (0.028157×10^9)
Steepness h	0.22248 (0.000522)
Amplitude of seasonality a	0.316975 (0.034649)
Closure effect on January q_{Jan}	0.298011 (0.06278)
Von Mises mode of monthly recruitment θ	2.2748 (0.303427)
Von Mises variance of monthly recruitment κ	1.210694 (0.149154)

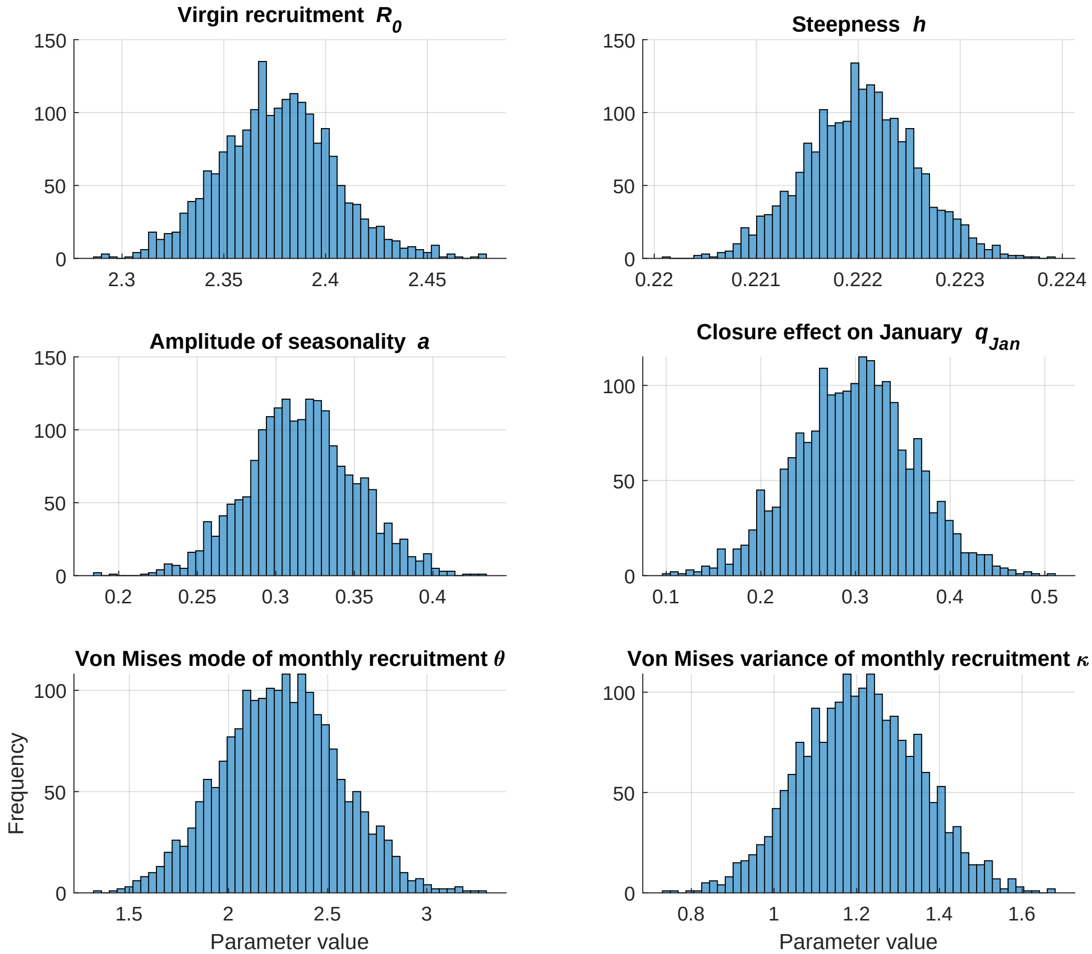

Figure C.4: MCMC parameter estimates for the six main parameters from the model

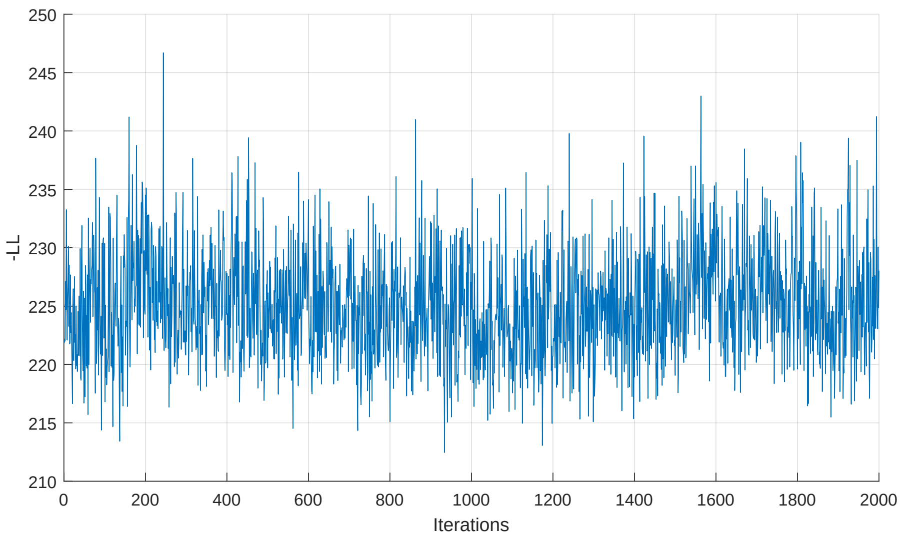

Figure C.5: MCMC –LL trace for the model

Appendix D Fishery Independent Otter Trawl Survey: Preliminary Results

Emily Maher and Jason McGilvray

D.1 Summary

The fishery independent otter trawl survey was completed in October 2021. One objective of the survey is to determine abundance and recruitment of scallops. Three chartered commercial vessels sampled 347 sites between Yeppoon and Noosa over 31 nights. The survey was spread out over 18 different survey areas including the six scallop replenishment areas (SRAs). Adjusted numbers of scallops were less in six out of the 18 survey areas compared to the 2020 survey (mostly in the southern survey areas). The other 12 survey areas (all north of 24° 30' S) had higher adjusted numbers of scallop compared to the 2020 survey. It should be noted that more sites were sampled in seven of those 12 areas in the 2021 survey compared to the 2020 survey. The adjustment factor of Vessel 3 that sampled in primarily the northern offshore survey areas was greater in 2021 compared to 2020 (Table 2).

D.2 Methods

D.2.1 Survey design

The survey is conducted in October which is after the scallop winter spawning season and within the historic southern trawl fishery closure. The scallop fishery is broken up into smaller survey areas (Figure D.1). The number of sites sampled within a survey area is determined by the commercial catch and effort reported in that area.

Sites are randomly selected and sampling consists of a one nautical mile tow, using common east coast commercial prawn trawl fishery net configurations. Survey staff count every scallop.

D.2.2 Vessel calibration

Side-by-side trawls are completed in a pre-determined, randomised arrangement to enable comparison of catch rates from each of the different boats. In 2021, 11 sites were sampled within the Hervey Bay A SRA. The data was used to calculate the vessel adjustment factor for each vessel and is based on the vessel (Vessel 1) with the longest history in undertaking the survey.

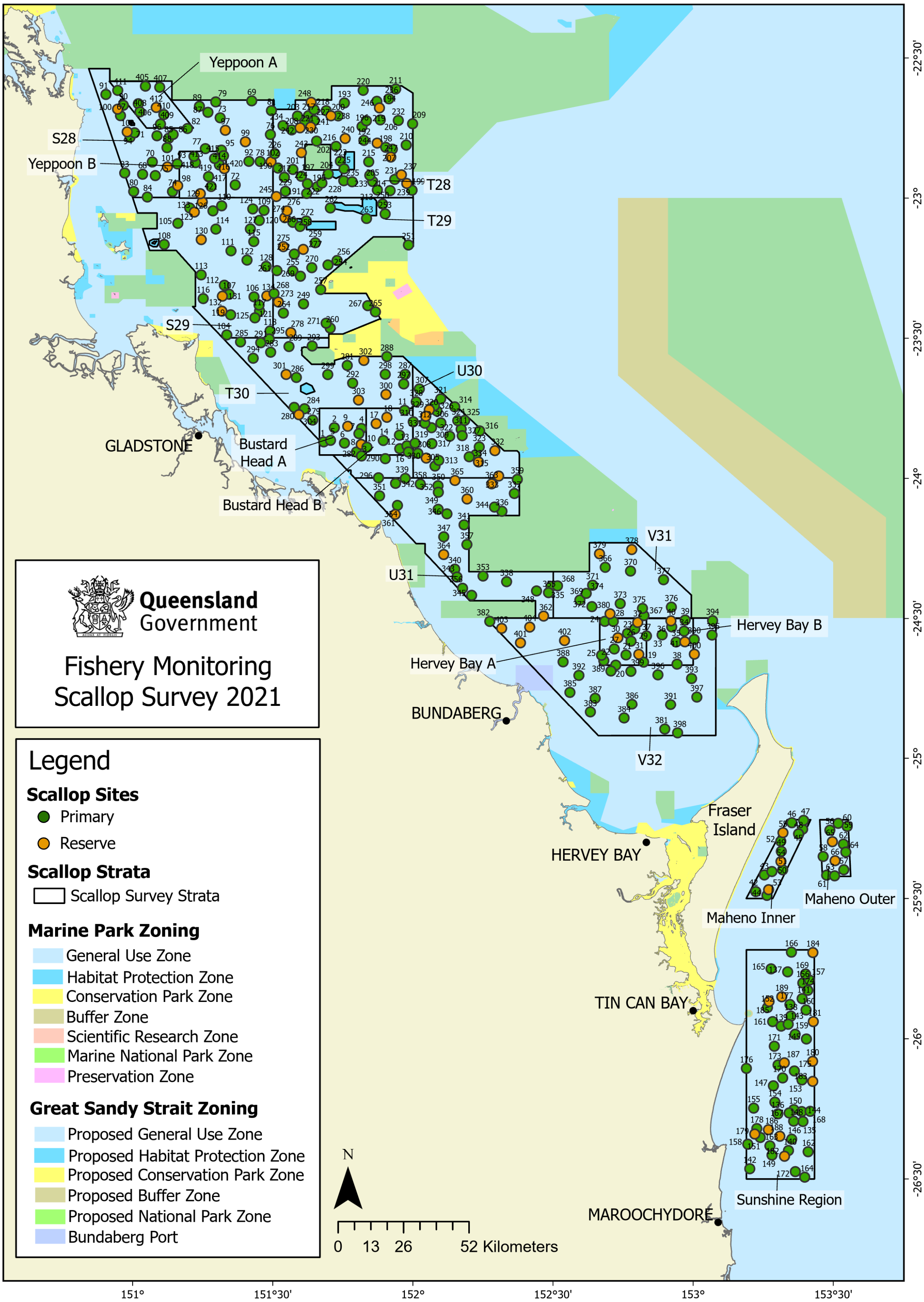

Figure D.1: Randomly selected sites within each 2021 survey area (green dots). Orange are reserve sites

D.3 Results

The vessel specific calibration multiplier was applied to the total catch of scallops at each site (Table D.1). The adjustment factors used to calculate adjusted numbers of scallop for all recent surveys (2017-2021) are provided (Table D.2). The number of scallops caught at each site were adjusted (based on the vessel adjustment factor), then added together to get a total for each survey area (Table D.3).

	Number of calibration trawls in Hervey Bay A	Mean total density (number/ha)	Adjustment factor 2021
Vessel 1	11	27.100	1.000
Vessel 2	10	13.275	2.041
Vessel 3	11	9.358	2.896

Table D.1: Estimated mean density of scallops during calibration shots and calibration multiplier (adjustment factor) (2021 survey)

	2017	2018	2019	2020	2021
Vessel 1	1.000	1.000	1.000	1.000	1.000
Vessel 2	3.299	0.992	1.226	1.648	2.041
Vessel 3	6.435	1.650	1.103	1.256	2.896

Table D.2: Adjustment factors (2017-2021 surveys)

Area	2017*		2018		2019		2020		2021	
	Shots	Scallops	Shots	Scallops	Shots	Scallops	Shots	Scallops	Shots	Scallops
Yeppoon A	14	11642	7	5262	13	5078	7	124	7	173
Yeppoon B	4	5123	8	7346	7	10767	7	5933	7	28413
S28	45	28358	30	19195	31	8012	30	4546	27	14903
T28	52	11721	42	3809	35	1163	34	717	46	4998
S29	18	5020	27	10076	22	4819	23	1950	25	2202
T29	14	452	22	4788	23	4208	17	2709	24	4763
T30	19	2301	15	2043	18	3214	15	874	21	4573
U30	6	82	22	1616	17	373	17	362	24	718
Bustard Head A	9	3420	8	8262	3	651	7	620	7	1404
Bustard Head B	6	2448	8	31342	7	5525	8	887	7	4230
U31	11	2810	17	9689	23	520	22	303	23	339
V31	10	272	9	1821	11	851	9	8	12	593
Hervey Bay A**	33	32745	31	48621	32	37555	30	7077	32	4999
Hervey Bay B	6	597	7	690	7	1449	7	446	7	112
V32	25	13943	17	8413	17	1344	24	1198	17	208
Maheno Outer	9	577	9	183	9	527	9	435	5	57
Maheno Inner	***		17	2531	15	8423	10	179	11	77
Sunshine Region	36	22464	37	6191	40	15250	50	17245	45	2976
Totals	**317**	**143975**	**333**	**171878**	**330**	**109729**	**326**	**45613**	**347**	**75742**

Table D.3: Adjusted total catch of scallops and number of shots completed within each survey area, 2017-2021. * Total shots and scallops caught in 2017 does not include two Marine National Park survey areas. ** Hervey Bay A survey area is the calibration location (i.e. multiple shots occurred through the same sites). *** Maheno Inner survey area added in 2018. In 2017, Maheno Outer stratum was named Maheno