Stock assessment of Ballot's saucer scallop (*Ylistrum balloti*) in Queensland

July 2020

Queensland
Government

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Contents

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 fishery currently harvests scallops by commercial otter trawling, with a minimum shell height of 9 cm.

The main fishing ground for saucer scallops is mostly between Yeppoon and Hervey Bay in Queensland waters. Here they are a single population (stock), 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 managed separately. Assessment results were focused for region 3.

For the 2020 fishing year, region 3 scallop fishery management is characterised by a total allowable effort quota (effort units), six permanently closed Scallop Replenishment Areas and a no-take scallop closure from 1 May to 30 November (however ,trawling for other species can occur).

Before 2002, harvest of legal sized scallops were normally ≥ 800 tonnes of meat weight per fishing year, and peaked in 1993 at over 1800 tonnes. Since 2011, annual harvests were mostly ≤ 400 tonnes. Harvest of legal sized scallops in the 2018 and 2019 fishing years (2019 fishing year means 1 November 2018 to 31 October 2019) were 163 tonnes and 246 tonnes (meat weight) respectively for the management stock in region 3.

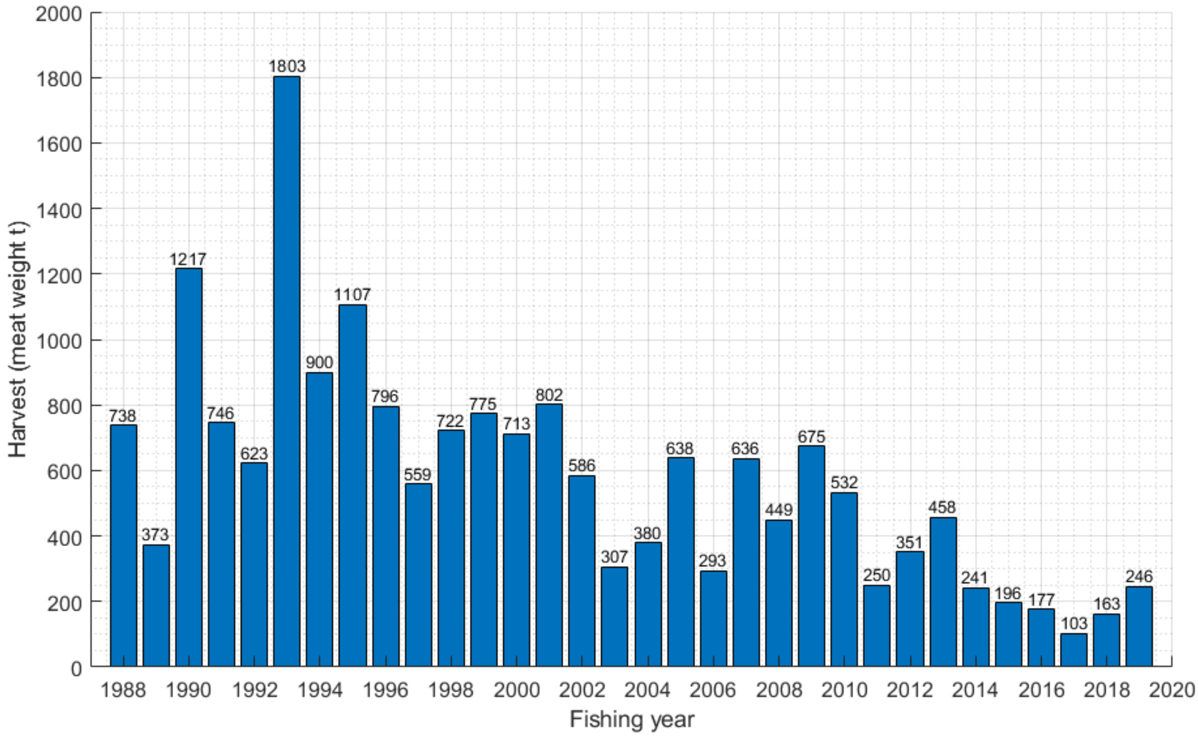

Figure 1 Annual scallop harvests from waters on the main fishing ground between Yeppoon and Hervey Bay along the east coast of Queensland (region 3)

Abundance measures of standardised catch rates of legal-sized scallop for region 3 declined sharply from 18 baskets per boat day in November 2018, to 4 baskets per boat day in April 2019.

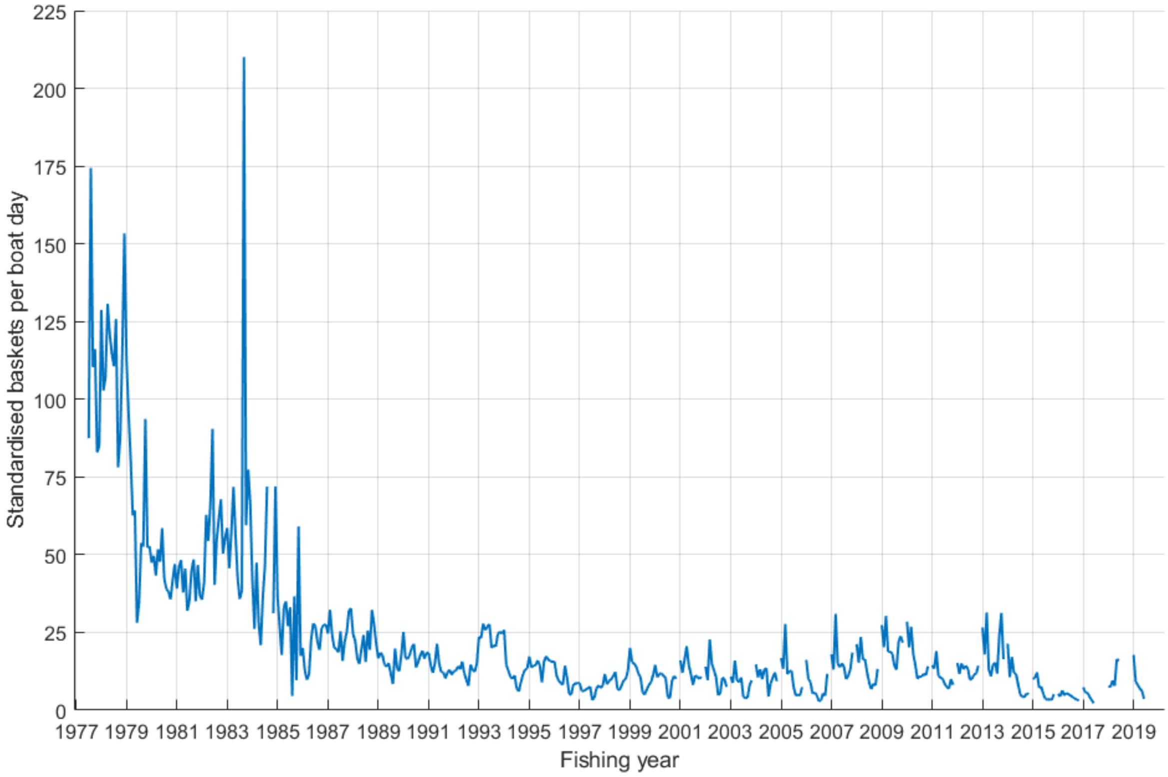

Figure 2 Standardised monthly catch rates (1977–2018) for region 3

Commercial sized scallop density (number of legal sized scallops per hectare in October) from the fishery independent survey decreased from 93 to 56 scallops per hectare from 2018 to 2019.

Figure 3 Mean modelled commercial scallop densities per hectare

The region 3 stock assessment input data were monthly harvest totals (1956–2019), monthly standardised catch rates (1977–2019), and October survey density (1997–2000 and 2017–2019). The assessment was run contrasting a traditional natural mortality estimate of 0.0900 per month, against a new updated estimate of 0.1217 per month.

A previous stock assessment for the region 3 component of the biological stock was published in 2020. Results suggested the 2018 spawning biomass was at 22% (95% confidence interval 17–32%) of unfished level in 1956.

When the stock assessment model was run with the natural mortality of 0.0900 per month, the estimated 2019 spawning biomass was at 14% of unfished biomass in 1956 (95% confidence interval 11–22%). Results using the new higher estimate of natural mortality suggested that the 2019 spawning biomass was at 17% of unfished biomass in 1956 (95% confidence interval 11–24%). The 95% confidence interval shows that the influence of the change in natural mortality is insignificant. In addition, spawning biomass estimates declined from 2018 to 2019, mainly due to a sharp decline in catch rates in 2019, as well as a decline in survey scallop density from 2018 to 2019.

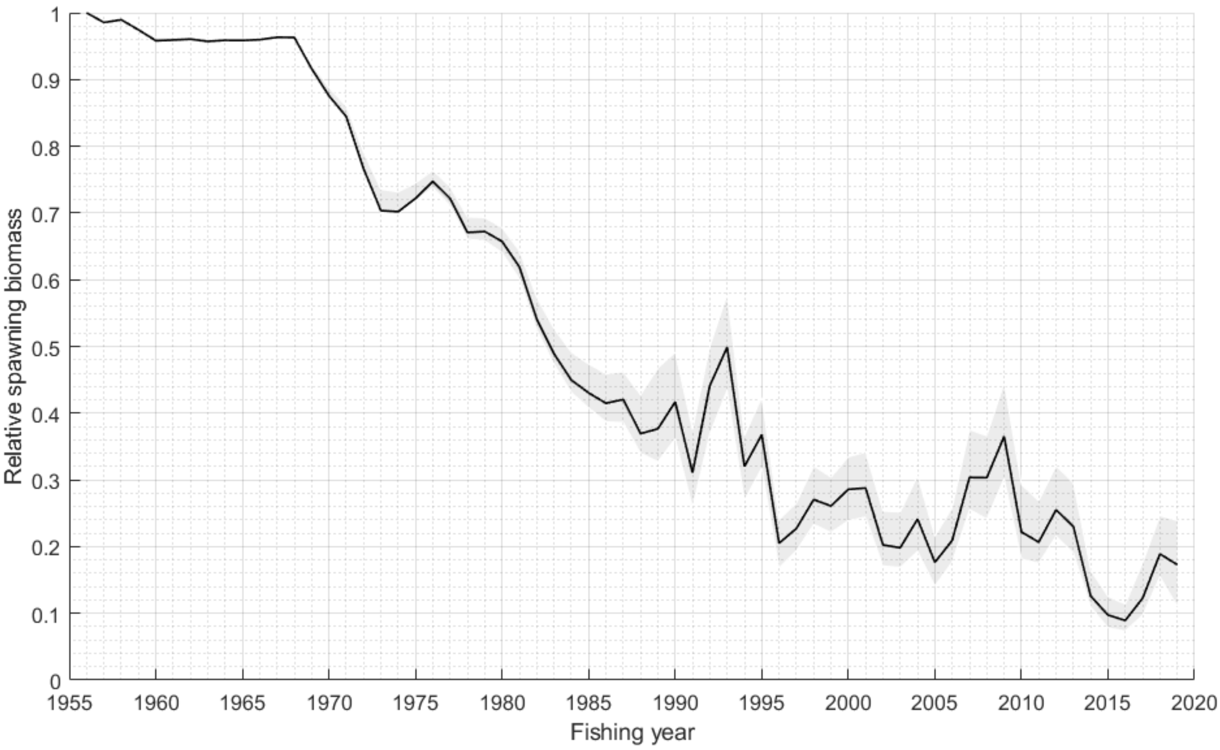

Figure 4 Spawning biomass ratio (±95% CI) from 1956 to 2019 for updated natural mortality estimate

Current allocated effort units in the scallop fishery in region 3 are 118 635 effort units. Forecasts predicted that 80 000 effort units (1454 boat days) were required for 8 years to build the biomass to 40% of unfished biomass (related to levels at 1956). Estimated annual harvest under this scenario of 80 000 effort units in 2020 would be 150 tonnes (meat weight). If the spawning biomass rebuilt to 40% of unfished spawning biomass, then the potential yield from the fishery was estimated to be around 454 tonnes. This is in contrast to forecasts estimated under the current effort, which indicated that spawning biomass would take 20 years to reach 42% of unfished spawning biomass.

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

Indicator	Result
Current spawning biomass (relative to unfished) 2019	17%
Current harvest (tonnes meat weight) 2019	246 tonnes
Current scallop effort units	118 635 effort units
Harvest proportions	All commercial otter-trawl
Maximum sustainable yield biomass / unfished biomass	42%
Potential harvest at B_{40}	454 tonnes (391–498 tonnes)
Effort units to build to B_{40}	80 000 effort units
Harvest in 2020 with effort units of 80 000	150 tonnes
Time to build to B_{40}	8 years

Acknowledgements

This work was overseen by a 'project team' committee that consisted of the following scientists and managers: Tony Courtney, Sue Helmke, Eddie Jebreen, Jason Mcgilvray, Michael O'Neill, Anthony Roelofs, Darren Roy, Samuel Williams, Joanne Wortmann and Wen-Hsi Yang. The role of the committee was collaborative to share interpretation and decision making on information and results.

In addition to the role of the committee, the project would like to thank Genevieve Phillips and Ashley Lawson for the extraction and supply of the Queensland commercial harvest data, Tony Courtney for the provision of harvest data and the investigation of catch records during closed periods in the years 2018 and 2019, Wen-Hsi Yang for the provision of catch rate data and harvest data, Tony Courtney and Wen-Hsi Yang for the provision of 2019 survey density data and Tony Courtney, Wen-His Yang and George Leigh for the updated estimate of natural mortality.

The authors would also like to acknowledge and thank the many fishers and scientists who have contributed to past research on saucer scallop.

Thank you to Alise Fox for report edits and review.

We would finally like to thank Graeme Bolton and the project team for reviewing and providing comments on parts of the draft report.

This assessment was funded by the Queensland Department of Agriculture and Fisheries.

Glossary

Term	Definition
B	Exploitable biomass: the combined weight of legal sized scallop.
B_0	Mean equilibrium virgin exploitable biomass: average biomass level before fishing.
B_{60}	Exploitable biomass equal to 60 % of B_0. This is the long term rebuilding target reference point.
B_{40}	Exploitable biomass equal to 40 % of B_0. This is an initial (interim) rebuilding target reference point.
B_{20}	Exploitable biomass equal to 20 % of B_0. This is a potential limit reference point.
B_{MSY}	The exploitable biomass that can support a potential harvest of MSY.
Ballots' saucer scallop	*Ylistrum balloti*, formerly *Amusium balloti,* referred to as saucer scallop in this document.
eu	effort units= standardised boat-days × standardised hull units.
E_y	Number of eggs (spawning egg production) in fishing year y.
Density	Number of scallops per hectare.
F_{B60}	Instantaneous fishing mortality with harvest rate for equilibrium exploitable biomass equal to 60 % of B_0
F_{B40}	Instantaneous fishing mortality with harvest rate for equilibrium exploitable biomass equal to 40 % of B_0.
F_{B20}	Instantaneous fishing mortality with harvest for equilibrium exploitable biomass equal to 20 % of B_0.
F_{BMSY}	Instantaneous fishing mortality with harvest rate for equilibrium MSY.
Fishing year	Fishing year y was from November until October the following year. For example, fishing year label 2019 was from November 2018 to October 2019, where November was fishing month 1 and October was fishing month 12.
FRDC	Fisheries Research and Development Corporation www.frdc.gov.au.
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.
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.
SRA	Scallop Replenishment Area.
SST	Sea surface temperature
t	Tonnes of scallop meat weight.

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, Officer, 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 likely to be less connected to the main ground. 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 5). There are six Scallop Replenishment Areas (SRAs) inside region 3.

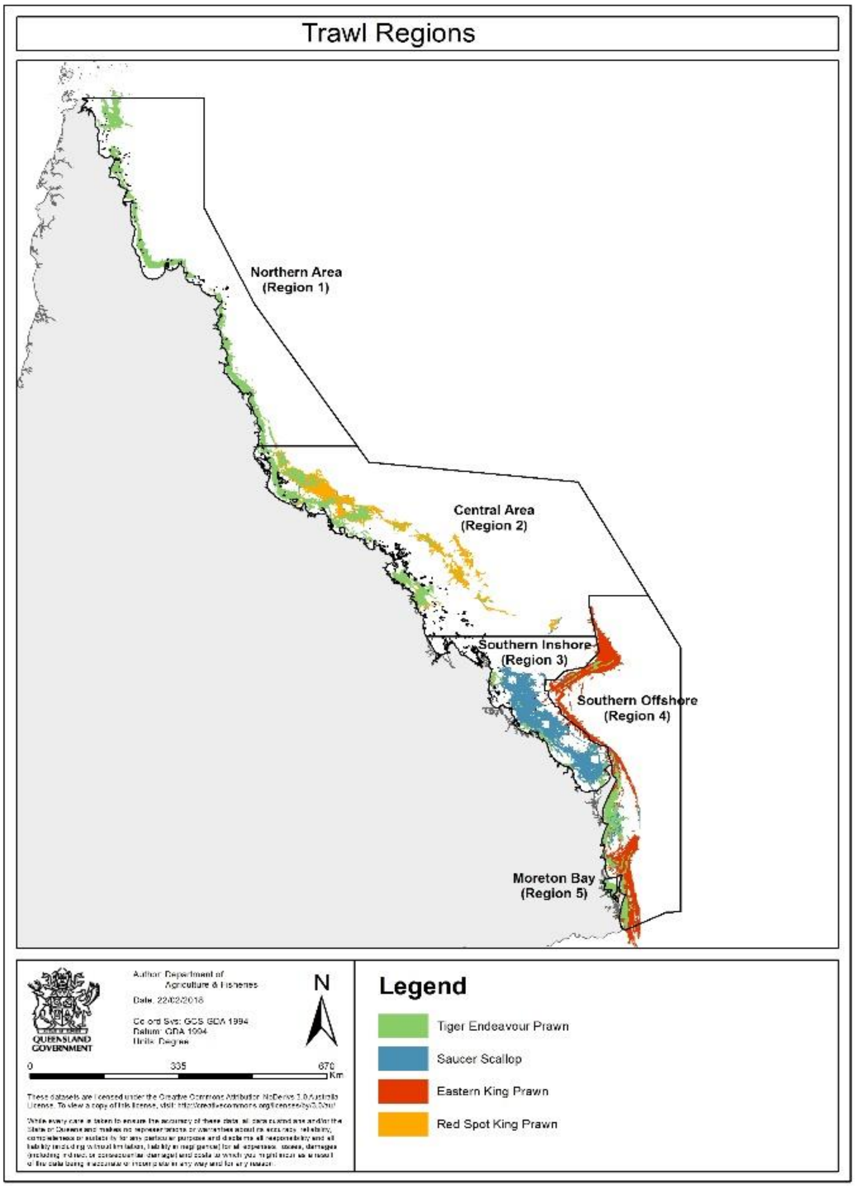

Figure 5 East coast trawl fishery divided into five management units (Department of Agriculture and Fisheries 2019). The scallop sector is region 3, south of 22° S to Hervey Bay.

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 in 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 often quad-gear (with some triple and five net-gears), spread by kilfoil/lourve otter boards, with square-mesh net cod-ends for bycatch reduction and turtle exclusion devices. 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).

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 (O'Neill et al. 2020). For regular assessments, O'Neill et al. (2020) recommended the model for region 3 for ease and consistency. This stock assessment used the model for region 3 from O'Neill et al. (2020) with updated data to include the 2019 fishing year. We provide estimates of sustainable harvests for management region 3 that will maintain the Queensland fishery and support implementation of Queensland's Sustainable Fisheries Strategy 2017–2027 (Queensland Government 2017).

Management of scallop fishing has varied over time (Table 2, O'Neill et al. (2020)). Harvests before 1987 had smaller minimum legal size (MLS) limits (commercial shell height of less than 9 cm). From 1987, seasonal minimum legal sizes of 9 cm and 9.5 cm 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 2 Management changes applied to saucer scallop in Queensland waters

Description	Date	Management Plan
Shell Height (SH)	Pre-November 1980	No minimum legal size (MLS)
	November 1980	8 cm shell height (SH)
	July 1984	8.5 cm SH
	October 1987	9 cm SH
	March 1989	9.5 cm SH April–October, 9 cm SH November–March
	May 1989	9.5 cm SH May–October, 9 cm SH 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
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

On 1 December 2019 a scallop effort cap of 118 635 effort units (2145 boat-days) was implemented for region 3. The scallop fishery is closed May to November, with scallop replenishment areas permanently closed.

The spatial structure of the scallop fishery is shown in Table 3. K'gari zone is located outside of the main scallop fishing grounds. K'gari is associated with irregular and infrequent scallop catches. Southward ocean currents do not support a recruitment linkage from K'gari to the main fishing grounds Hervey Bay and north.

Table 3 A summary of the spatial structure of the scallop fishery in region 3, separated into zones and areas. SRA means scallop replenishment area

Zone	Area
Yeppoon	Yeppoon Yeppoon SRA A (YA) Yeppoon SRA B (YB)
Bustard Head	Bustard Head Bustard Head SRA A (BHA) Bustard Head SRA B (BHB)
Hervey Bay	Hervey Bay Hervey Bay SRA A (HBA) Hervey Bay SRA B (HBB)

The aim of this stock assessment was to update the model for region 3 from O'Neill et al. (2020), with the addition of 2019 harvest data, the results from the 2019 fishery independent surveys, and the updated estimate of natural mortality from Courtney et al. (2020).

Estimations are made for historical spawning biomass ratios, reference points, and forward projections for levels of fishing effort. This model defines the scallops as a whole stock and does not include environmental effects.

2 Methods

Fishing year is defined as the year from November until October the following year. For example, fishing year label 2019 was from November 2018 to October 2019, where November was fishing month 1 and October was fishing month 12.

Unfished biomass is defined as the biomass pre-1956.

2.1 Data sources

Data sources included in this assessment are detailed in Table 4 and are described in more detail in the following sections.

New data in this stock assessment compared to the previous in O'Neill et al. (2020) were:

- Commercial harvest data for the 2019 fishing year
- Standardised catch rates up to and including the 2019 fishing year
- The inclusion of the 2019 survey density data (number of scallops per hectare) for age group zero plus and one plus as per FRDC project 2017-048
- The updated estimate of natural mortality from tagging experiments in FRDC project 2017-048

Table 4 Data inputs for the population model

Data	Years	Source
Commercial	1988–2019	CFISH - Logbook data collected by Fisheries Queensland
Fishery-dependent survey	1997–2000, 2017–2019	Agri-Science Queensland, most recent survey data as per FRDC project 2017-048
Natural mortality		Courtney et al. (2020)

2.2 Harvest

The most recent and corrected monthly commercial catch data from commercial logbook records for saucer scallops were used for this stock assessment. Harvest data for model input was for 1956–2019 fishing years. There were some problematic catch records during closed periods, mainly in 2018 and 2019 (Appendix 6.1). For this stock assessment, the catch for the closed months recorded in the logbook data was included in the harvest data for model input.

2.3 Survey

A fishery independent trawl survey provided the scallop density data (number of scallops per hectare) for 2019 (FRDC project 2017-048). The survey focused on scallops grouped by age (0+ or 1+, depending on their size) in October of 2019. Aged densities 0+ were for shell heights < 7.8 cm, and aged densities for ≥ 1+ were for shell heights ≥ 7.8 cm The densities of legal sized scallops (shell heights ≥ 8.8 cm) were determined from the survey data The densities were scaled up by a survey catchability value of 1/0.6205 (Joll and Penn 1990). Adjustment of densities to other catchability values is by × 0.6205, and then divided by the different catchability value, e.g. of 0.2, 0.3, or 0.4. The model was run for catchability values of 0.2, 0.3 and 0.4. Results for catchability value of 0.3 were shown in this report. Catchability values of 0.2 and 0.4 generated similar results.

2.4 Standardised catch rates

The datasets and methods for the catch rate standardisations were collated and developed from the projects O'Neill et al. (2005), O'Neill and Leigh (2006), (Campbell, O'Neill, et al. 2010), Campbell et al. (2012), Yang et al. (2016) and O'Neill 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. The catch rate standardisation was programmed in Genstat (VSN International 2017)

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). See Appendix 6 for trends in vessel gears from 1988–2019 and changes in fishing power from gear changes, technology upgrades and hours fished from 1988–2019.

The catch rate standardisation followed analysis 3 and 4 in section 3.1 of O'Neill et al. (2020). There were two components to the catch rate standardization, one component to standardize catch rates for 1988–2019, and one component to standardize catch rates from 1977–2019 using parameter estimates from the first standardisation.

Catch rates were standardised for 1988–2019 (analysis 3 from O'Neill et al. (2020)) using:

- Log(baskets) ≈ fishingyear*fishingmonth*area + loghours + loghp + logspeed + sonar + gps + nettype + ggear + boards + random(boat) + random(grid)

where area = Yeppoon, Bustard Head, Hervey Bay, hours=hours fished; hp=engine horsepower, ggear=ground gear, nettype=net type and boards=board type.

The catch rates for 1988–2019 were standardised for a modern-day boat. This means that the standardisation factors included:

- Use of GPS and sonar
- Ground gear of drop chain
- Net type of quad gear
- Hours fished equal to the average of hours fished for 2007–2019 (12.13 hours)
- Engine power equal to the average 2019 engine power of 344 HP
- Boat that matched the maximum annual-average fleet-vessel effect. (For this catch rate analysis, this was in 2007, and the boat number with fleet effect that was closest to this was boat number 165)

Catch rates were standardized for 1977–2019 using analysis 4 of O'Neill et al. (2020):

- Offsetlog = loghp*0.3647 + sonar*0.1536 + gps*0.03556 + (nettype.eq.3)*0.3850 + (nettype.eq.4)*0.3287 + (nettype.eq.5)*0.2530 + (ggear.eq.3)*0.03821 + (ggear.eq.4)*-0.09128 + (ggear.eq.5)*-0.23186
- Lognoffset = log(baskets) – offsetlog
- lognoffset ≈ fishyear*fishingmonth + loghours + random(boat) + random(grid)

Catch rates for 1977–2019 were standardised for a modern boat that is fishing for 12.13 hours per night and boat number equal to 332 (boat with fleet effect that matched the maximum annual-average fleet effect for this catch rate analysis. This was in 2007). Fishing year by month trend for January 1977 to October 2019, excluding K'gari data (i.e. only for region 3) was calculated. The result focused on a single fishing year × month catch rate index for region 3.

2.5 Natural mortality

Past stock assessments used a natural mortality estimate, *M*, of 0.0225 per week (0.0900 per month or 1.1700 per year) (Dredge (1985), from a tag-recapture experiment conducted in 1977 and 1978).

The updated estimate of natural mortality used for this stock assessment came from tag recapture experiments described in Courtney et al. (2020) and Appendix 6.2. The annual mean estimate of *M* for the whole fishery is 1.461 per year or 0.1217 per month for the logistic model from Courtney et al. (2020). Estimates from other statistical methods used in Courtney et al. (2020) were similar. This value is higher than the estimate of 0.0900 per month used for previous stock assessments.

Courtney et al. (2020) stated that it is difficult to explain the unexpected increase in the estimate of *M*. One explanation from Courtney et al. (2020) is related to increasing sea surface temperature (SST). They argue that sea surface temperatures in the southern end of the Great Barrier Reef, (where the Queensland scallop fishery is located), have warmed, on average by 0.12 degrees per decade since 1950 (Australian Government 2019). Courtney et al. (2020) used Western Australia as an example where warming temperatures have had a detrimental effect on the population dynamics of *Y. balloti* (Caputi et al. 2015; Joll and Caputi 1995; Lenanton et al. 2009).

In the model there was no seasonal variation in *M*. It was assumed *M* was constant in time, as in the 2019 model.

2.6 Population model

The non-spatial model for region 3 in O'Neill et al. (2020) was used for this stock assessment. This model described the scallops as a single stock in region 3. Environmental effects were not included. The model was an age-based population dynamic model that assessed scallops monthly from the fishing years 1956 to 2019, counting scallop age classes from one to 48 months (4-year life cycle). The model accounted for the processes of scallop births, growth, reproduction and mortality in every fishing year-month. The details of the population model are in Appendix 6.5.

The model estimated an indicator of scallop abundance for region 3 and reference points and projections for management procedures to support the Queensland Sustainable Fisheries Strategy. The model was written in MATLAB (MathWorks 2017).

Equilibrium reference points were calculated by standardizing boat-days according to a modern day vessel, i.e. a boat with 344 HP, fishing 12 hours a night, with sonar, GPS, quad gear and drop chain. This was for a boat of around 55 standardised hull units (effort units = standardised days × standardised hull units (O'Neill and Leigh, 2006)). The estimates assumed the 2018–2019 pattern of fishing, with SRAs closed. The estimates for the equilibrium reference points were medians from MCMC, with 95% confidence intervals calculated.

Target reference points for the fishery were defined as 40% unfished spawning biomass (B_{40}) as a proxy for Maximum sustainable yield (MSY). A series of forward projections were undertaken to provide a timeframe based on rebuilding to B_{40} 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 pattern of the proposed four-month fishery (closed May–November, open December–January, closed February, open April–May, SRA's permanently closed), 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 5):

Table 5 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
Higher example	275 000 eu

3 Results

3.1 Model inputs

3.1.1 Harvest estimates

Before 2002, annual harvests were normally ≥ 800 t of meat weight per fishing year, and peaked in 1993 at over 1800 t (Figure 6). Since 2011, annual harvests were mostly ≤ 400 t. The lowest annual historical harvests occurred in the years 2017 and 2018, when compulsory closure of the whole scallop fishery was implemented for the months May–October. Harvests in the years 2017–2019 were 103, 163 and 246 t respectively.

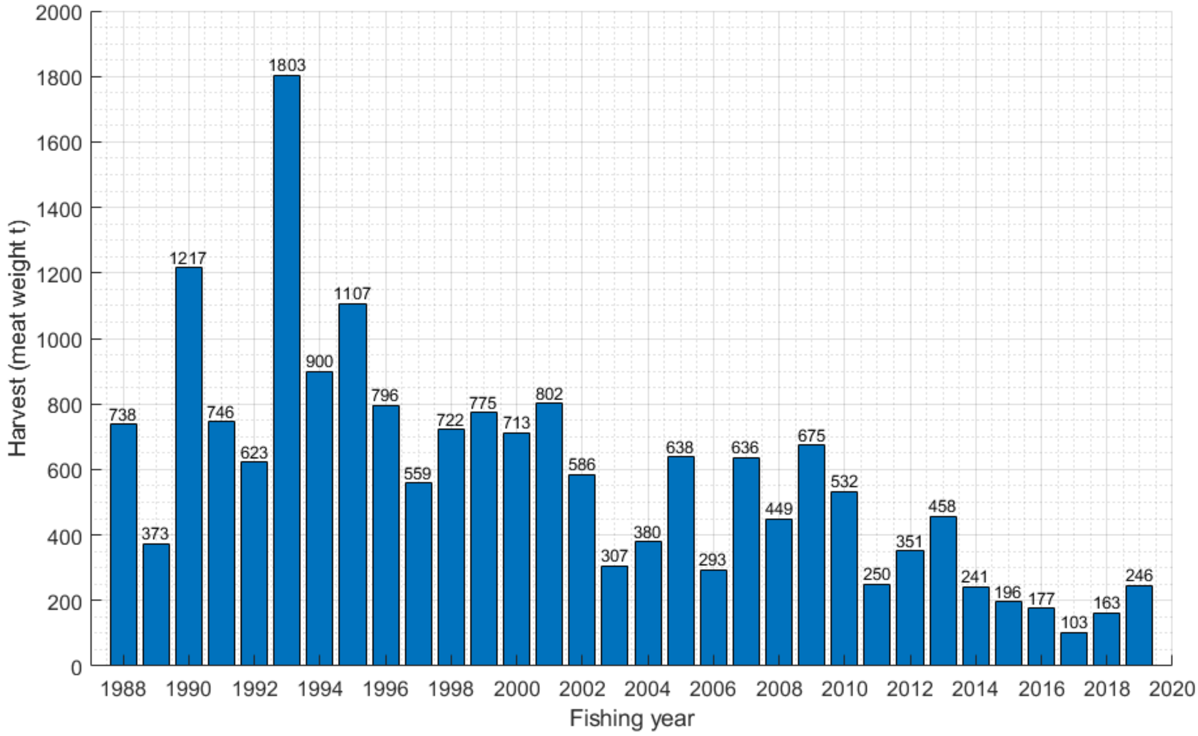

Figure 6 Annual scallop harvests from waters on the main fishing ground between Yeppoon and Hervey Bay along the east coast of Queensland (region 3)

Figure 7 shows the typical seasonal change in scallop harvest, with scallop harvests by month for the period 1956–2019. Since 2002, clear spikes in harvest occurred in the months of November and January. In the 2019 fishing year, 92% of the scallop harvest was taken in the months between November and January.

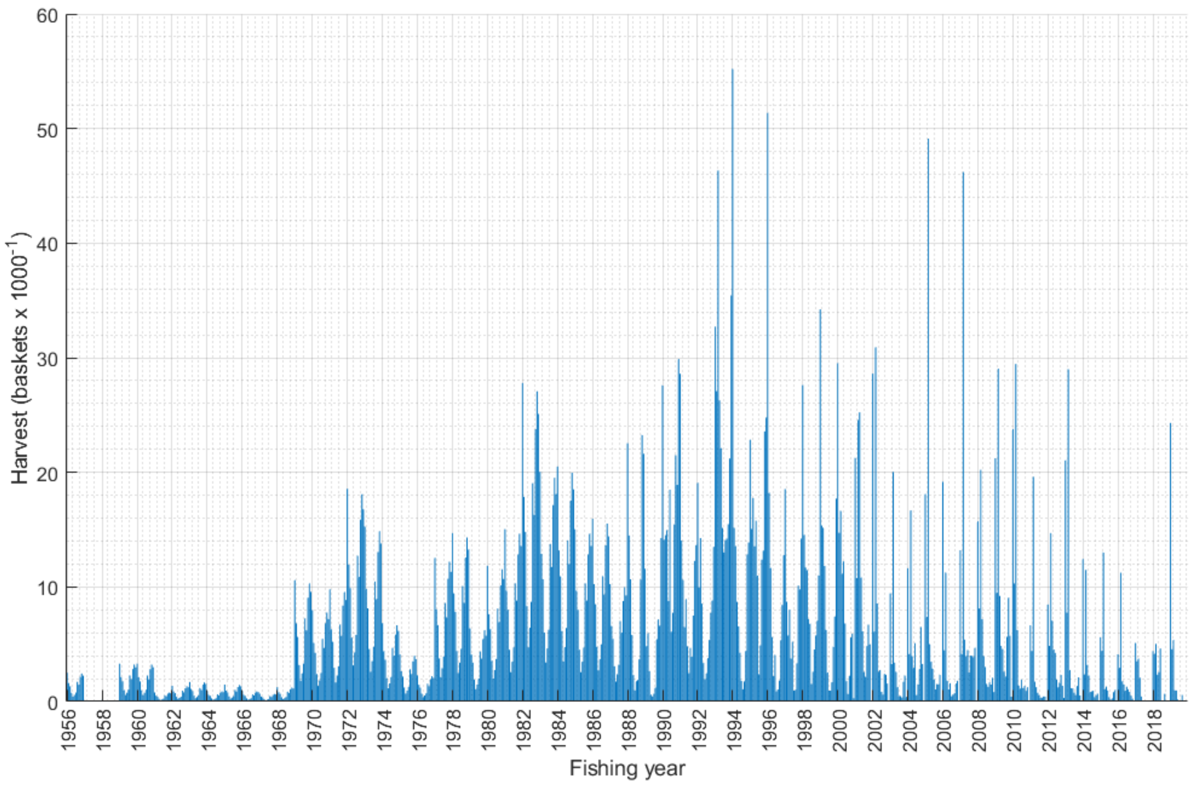

Figure 7 Monthly scallop harvests, from waters on the main fishing ground between Yeppoon and Hervey Bay along the east coast of Queensland (region 3)

3.1.2 Standardised catch rates

Catch rates declined steeply in the 2019 fishing year, from 18 baskets per boat day in November 2018, to 4 baskets per boat day in April 2019 (Figure 8). 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.

Standardised catch rates were lower than the reported-observed catch rate (Figure 9) due to the following factors:

- Area: Fishers move around to target areas with higher catch 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 2007–2019, namely 12.13 hours, catch rates were lower in the later years. This was because in the earlier years fishers were spending less time fishing for scallops (Figure 10).
- Gear: When catch rates were standardised according to gear settings of: ground gear = drop chain (most popular ground gear currently), net type = quad gear (since 2007 there was a shift to using quad gear), using GPS and sonar (most vessels used GPS by late 1990s) and average engine horsepower of 344 HP 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.

- 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.

Catch rate diagnostics are given in Appendix 7.1.

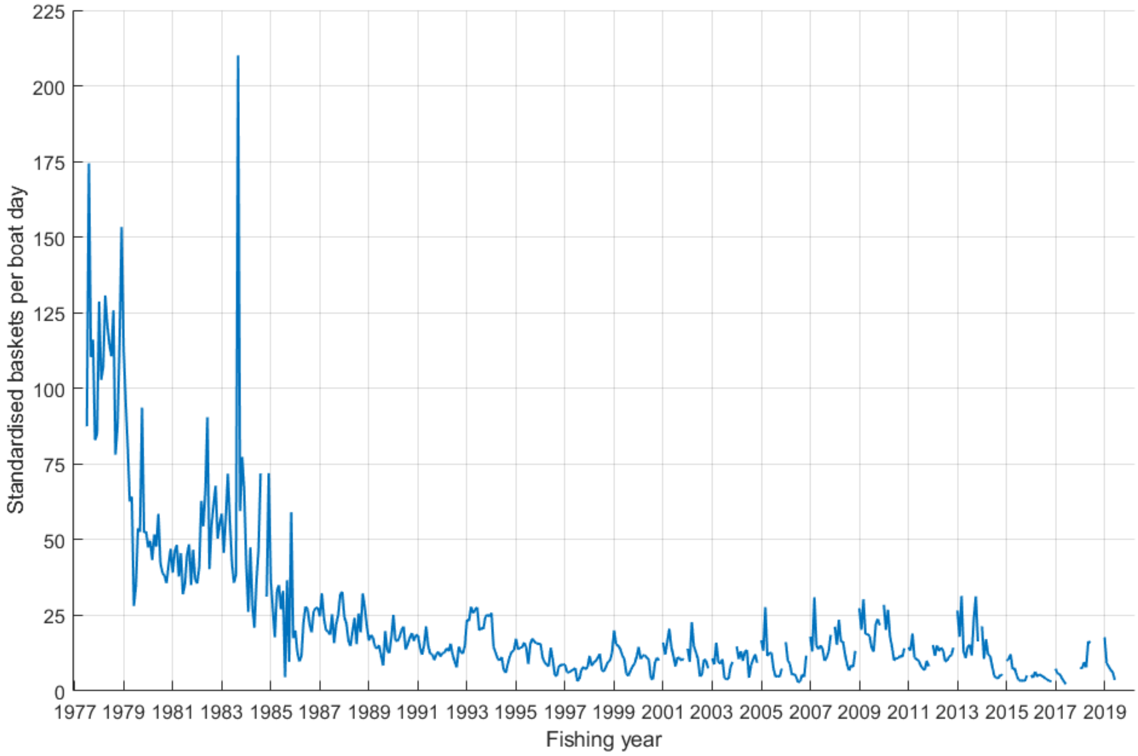

Figure 8 Standardised monthly catch rates 1977–2018 for region 3

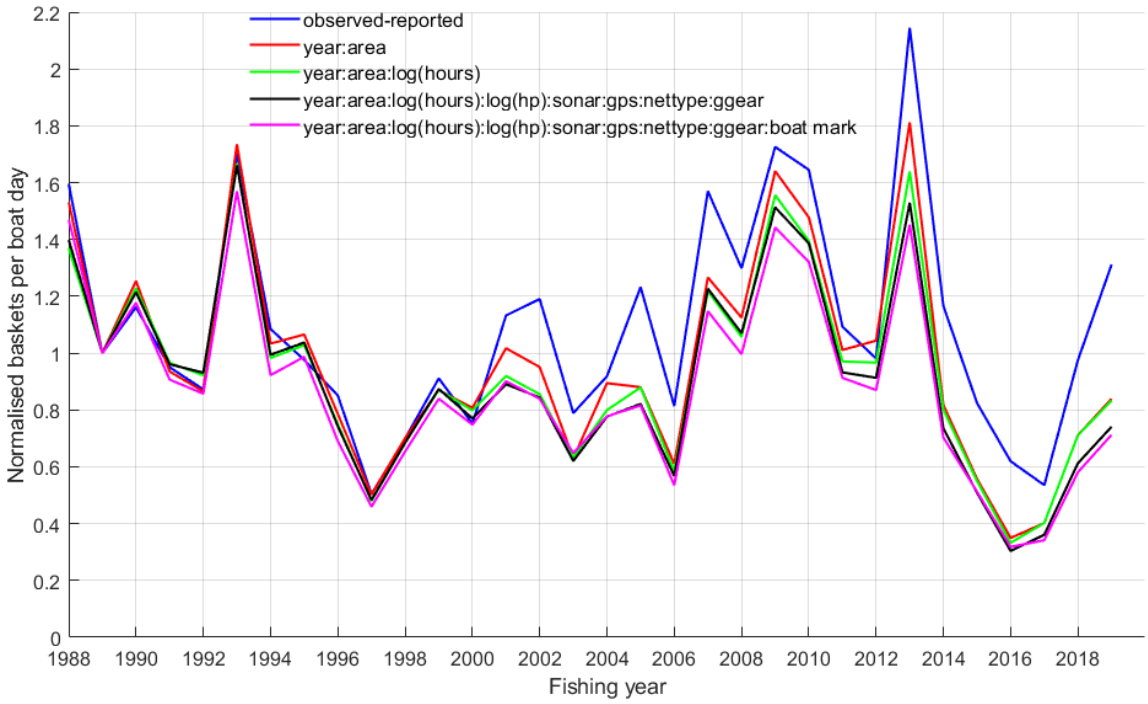

Figure 9 Relative influence of each factor in the annual commercial catch rate for saucer scallops for 1988–2019 for region 3. The legend in the figure shows which factors were included in the catch rate standardisation

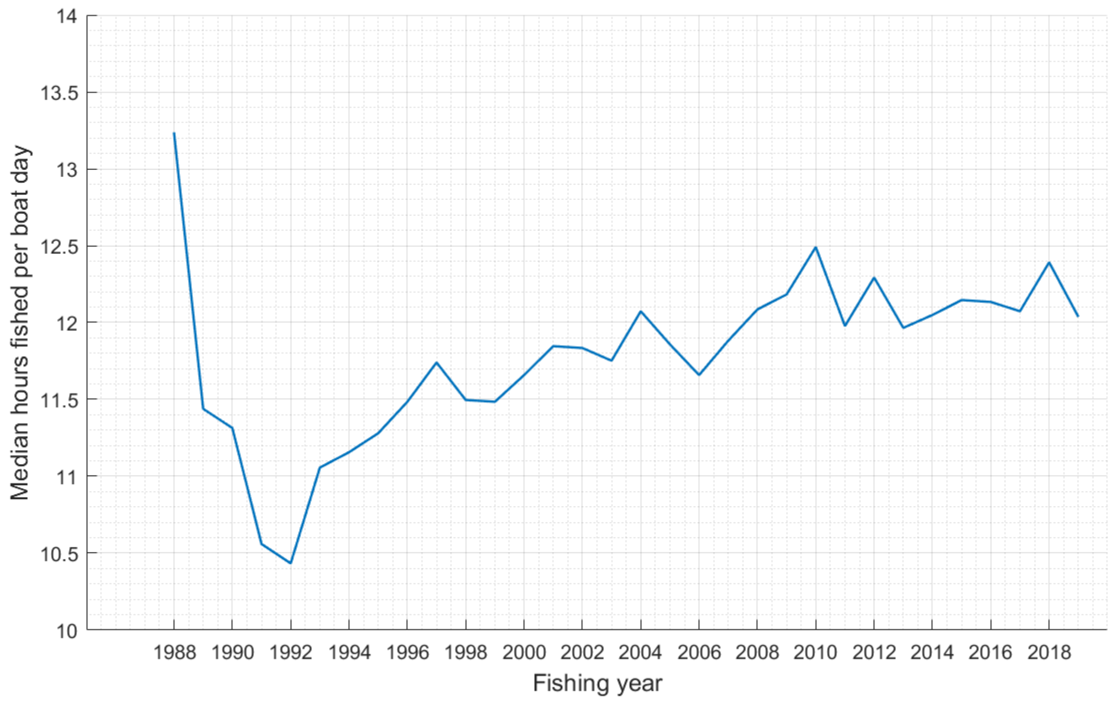

Figure 10 Median hours fished per boat-day from the linear mixed model data

3.1.3 Survey estimates

Scallop density (number of scallops per hectare) from the October survey decreased from 2018 to 2019 for both age 0+ and age 1+ groups (Figure 11). For age group 0+ the estimated density in 2019 was 10 scallops per hectare (down from 20 in 2018) and for age group 1+ the estimated 2019 density was 63 scallops per hectare (down from 146 in 2018). The density of legal sized scallops (calculated from the age 0^+ and age 1^+ surveys) decreased from 2018 to 2019 from 93 to 56 scallops per hectare (Figure 11). The area of region 3 was 1 256 473.72 hectares.

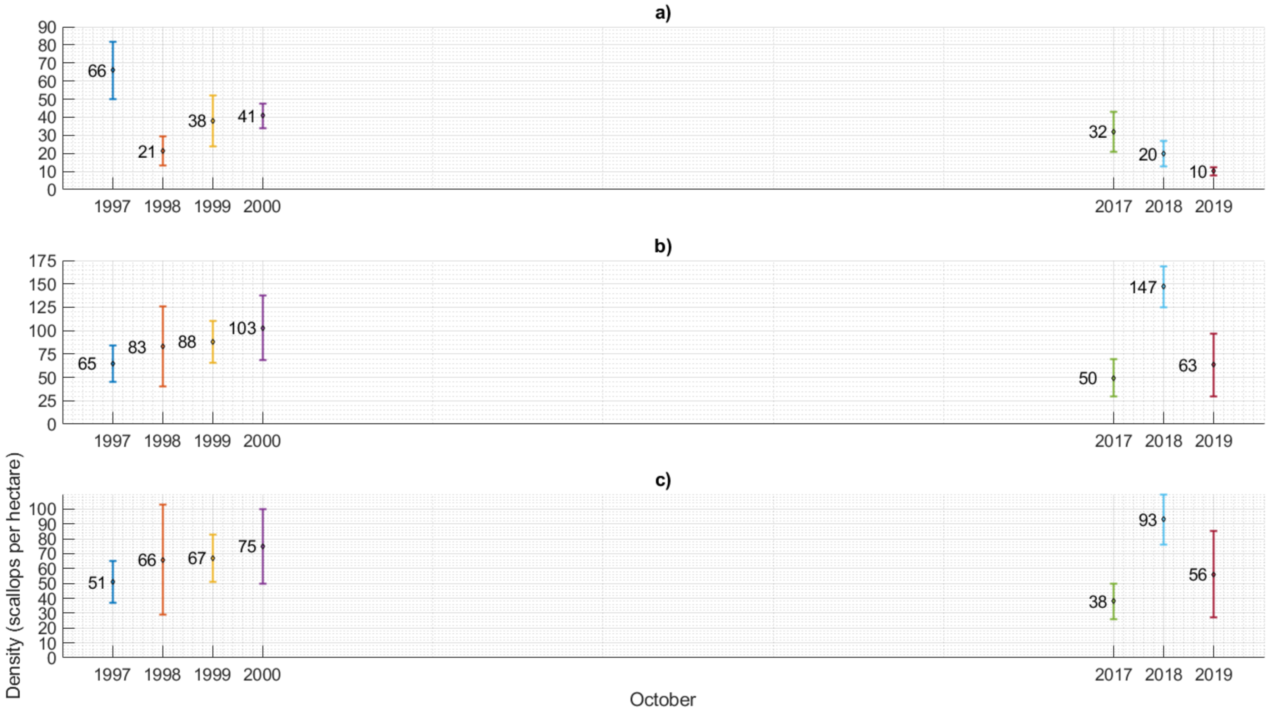

Figure 11 Mean modelled scallop densities per hectare by year for a) 0+ densities, b) 1+ densities and c) legal sized scallops. Standard errors are in parenthesis

3.1.4 Natural mortality

The model was run with the traditional estimate of *M* of 0.0900 (previous estimate used) per month and 0.1217 (updated estimate) per month (Figure 12). The 2019 spawning biomass was 14% and 17% of the unfished 1956 biomass respectively. For this stock assessment the updated value of natural mortality was used.

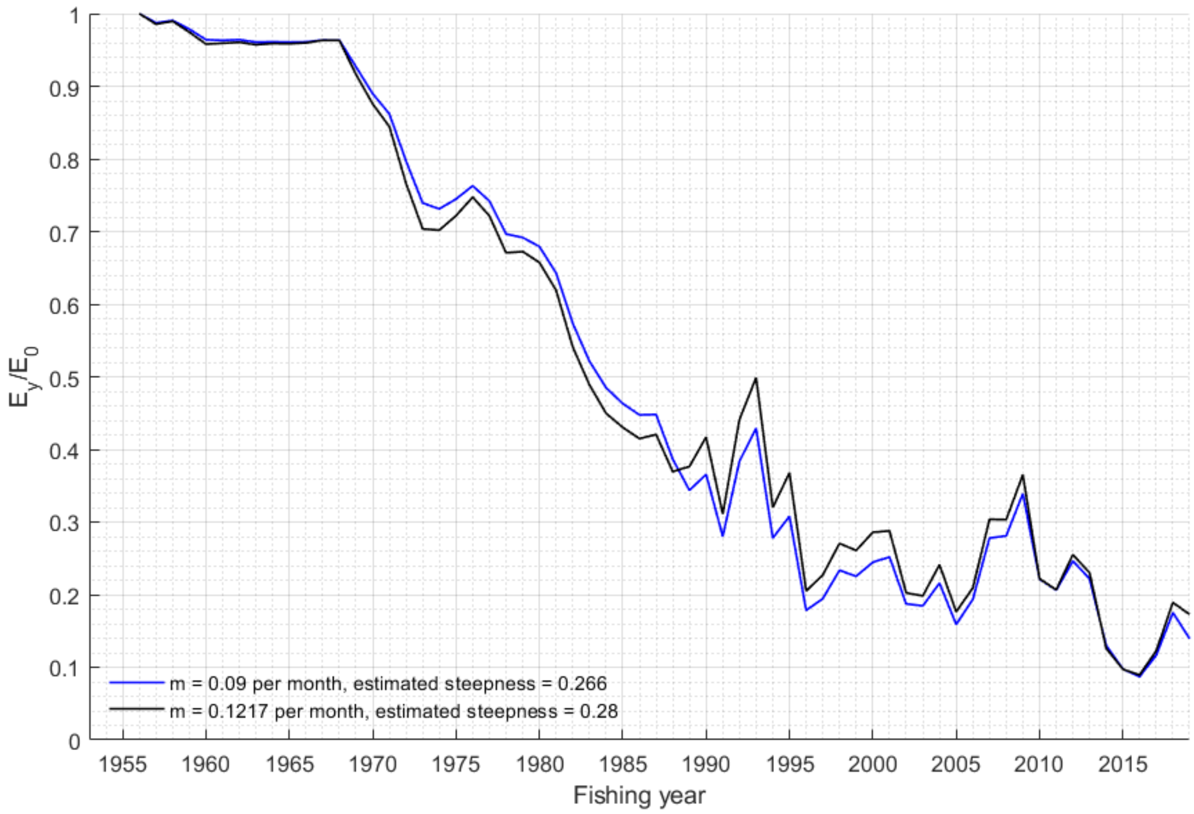

Figure 12 Spawning biomass natural morality estimate of 0.0900 and 0.1217 per month

3.2 Model outputs

3.2.1 Parameters

Parameter estimates for the six main parameters are shown in Appendix7.2. The steepness was estimated to be 0.2793. When the model was run with natural mortality of 0.0900 per month (2019 stock assessment), steepness was estimated slightly lower at 0.2664. MCMC parameter estimates and model diagnostics are shown in Appendix 7.2.

3.2.2 Biomass

The 2019 spawning biomass was 17% of unfished biomass with 95% confidence interval of 11–24% (Figure 13). Considering the upper bound being 24%, the result suggested the 2019 region 3 spawning biomass was below 30%.

Spawning biomass ratio dropped from 19% in 2018 to 17% in 2019. This is likely due to the sharp decline in catch rates in the 2019 fishing year (Figure 8) and the decrease in scallop density for age 0+ and age 1+ from the fishery independent trawl survey in October 2019 (Figure 11).

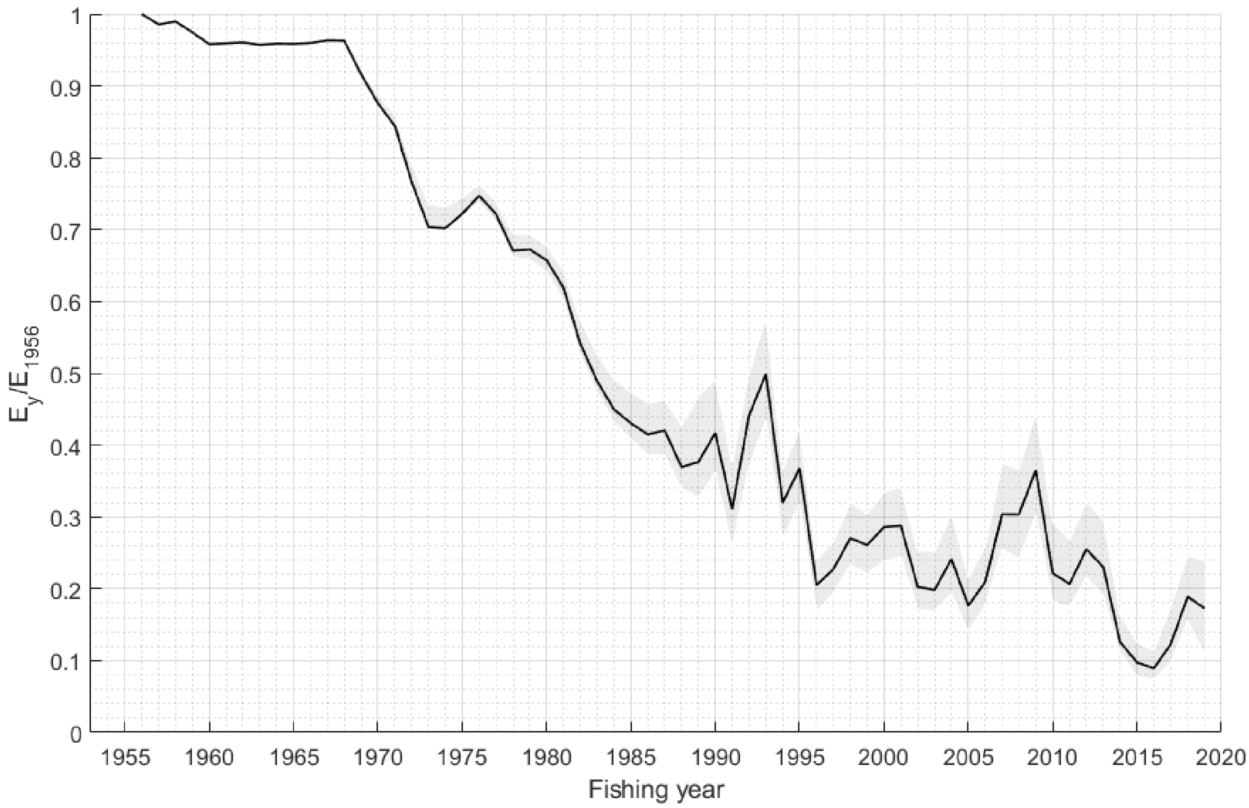

Figure 13 Spawning biomass ratio (± 95% CI) from 1956–2019

3.2.3 Targets

Maximum sustainable yield occurred at a biomass of 42% of unfished biomass (Table 6). The maximum sustainable yield is 456 t per year, with effort of about 140 000 effort units. If scallop biomass is at 40% unfished biomass, then an annual yield of 454 t under about 147 000 effort units is possible.

Table 6 Description of current and target harvest indicators. 95% confidence intervals are shown in brackets

Indicator	Result
Current spawning biomass (relative to unfished) 2019	17% (11–24%)
Current harvest (tonnes meat weight) 2019	246 t
Average 5 year harvest (tonnes meat weight) 2015–2019	177 t
Current scallop effort units	118 635 eu
Harvest proportions	All commercial otter-trawl
Maximum sustainable yield biomass (relative to unfished)	42%
Potential harvest at B_{40}	454 t (391–498 t)
Boat-days to maintain B_{40}	2674 boat-days (2480–2913 boat-days)
Effort units to maintain B_{40}	147071 eu (136411–160249 eu)
Potential harvest at B_{MSY}	456 t (394–499 t)
Boat-days to maintain B_{MSY}	2544 boat-days (2363–2796 boat-days)
Effort units to maintain B_{MSY}	139 948 eu (129 984–153 807 eu)
Potential harvest at B_{60}	409 t (358–439 t)
Boat-days to maintain B_{60}	1575 boat-days (1461–1710 boat-days)
Effort units to maintain B_{60}	86 644 eu (80 357–94 086 eu)

For the fishing efforts projected, except for the higher example of 275 000 effort units, the spawning stock generally increased (Figure 14). Under a high fishing effort of 275 000 effort units (or 5000 boat-days), the spawning stock declined.

Under no fishing, the spawning stock biomass ratio reached 40% of unfished biomass in 5 years.

For the current fishing effort of 118 635 thousand effort units, the spawning stock after 20 years reached 42% of unfished biomass. Under this effort scenario, harvest of 206 t is possible in 2020. This is less than the 2019 annual harvest of 246 t.

If the effort is reduced to 80 000 effort units, it will take 8 years to reach 40% unfished biomass. Under this scenario of 80 000 effort units, harvest of 150 t is possible in 2020. This is the second lowest annual harvest recorded. The only annual harvest lower than 150 t was in 2017 which was 103 t (Figure 6).

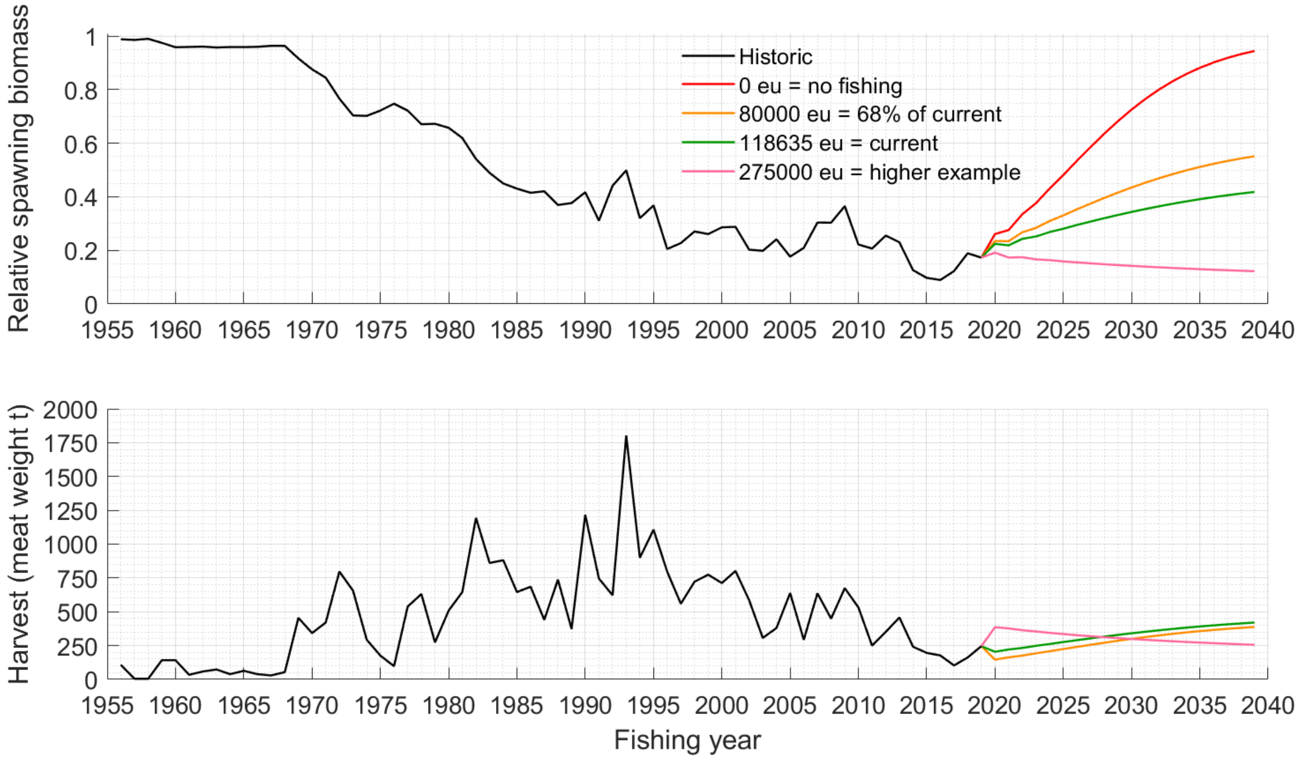

Figure 14 Forecasts of annual spawning biomass and harvest

4 Discussion

4.1 Stock status

Spawning biomass ratios in 2019 were still below the limit reference level of 0.2. In 2019 management changes to the scallop fishery included capping of fishing effort to 118 635 units. However, the scallop fishery remains overfished.

The model results provide support for additional Queensland Government management procedures. From the reference points and model projections, around 80 000 effort units will lead to 40% biomass in 8 years in the path to achieve the Sustainable Fisheries Strategy ecological objectives. The effort units equate to an annual harvest 150 tonnes of meat weight in the year 2020. This is the second lowest annual harvest in the scallop fishery ever.

The estimated recommended biological catches and fishing effort are the best available advice on what sustainable fishing pressure is for the scallop population.

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 remains unexplained. It was a challenge to estimate away from the theoretical (linear) low limit of 0.2 for steepness. Therefore, estimates of steepness and virgin recruitment were highly correlated. Further minor work is required to investigate low steepness, and possibly substitute the Beverton-Holt recruitment equation for a Ricker form (Haddon 2001).

4.3 Environmental impacts

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 the *Y. balloti*.

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.

The decision rules used to define total saucer scallop catch in this assessment and past assessments have included all four scallop species codes (codes 23270000, 23270001, 2327003 (mud scallop) and 23270005). If there is a genuine, recent move by industry to target and record mud scallop catch in closed months, then the definition (i.e. the codes) of scallop catch for future assessments needs to be altered.

4.4.2 Management

Management procedures need to control fishing efforts to increase scallop biomass.

The SRAs should remain closed in the short-term until some 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, O'Neill, et al. 2010).

Fishing effort 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 2019 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 effort is reduced to 80 000 units, then this will allow the population to build to 40% in 8 years. If spawning levels are at 40%, then the possible yield from the scallop fishery is 454 t. Without a reduction in effort units it is estimated that the stock will not recover to MSY 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. 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 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*.

The fishing year is getting smaller. The definition of a fishing year may need to change. The current definition of a fishing year is from November–October. However, fishing from 2019 does not commence until December.

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

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6 Appendix A: Model inputs

6.1 Harvest

There were some problematic catch records from the commercial logbook data during closed periods, mainly in 2018 and 2019. Most of these records were recorded as mud scallops (code 2327003), which the fishers are permitted to retain during the closure months. The decision rules used to define total saucer scallop catch in the past have included all four scallop species codes (codes 23270000, 23270001, 2327003 and 23270005). The contribution of mud scallop (2327003) to the overall reported catch of scallops from 1988–2019 in the scallop fishing grounds (i.e. 22–28° S) was less than 1%. In 2018 and 2019 there appeared to be some targeting of mud scallops during the winter months. For example, there were 673 baskets reported in July 2018 and 583 baskets reported in July 2019. It is unclear whether these are legitimate mud scallop catches or illegal saucer scallop catches recorded as mud scallop.

There were also some problematic catches in October 2018 (109 baskets) and September 2019 (134 baskets), which were recorded as saucer scallops (code 23270001) and/or 'scallop unspecified' (23270000).

In calendar year 2018, 1.6% of baskets were reported from closed months (807 baskets out of a yearly total of 51 757). In 2019, 7.4% of baskets were reported from closed months (777 baskets out of a yearly total of 10 511) – the majority of which were reported as mud scallop.

The reported mud scallops were mainly coming out of grid U30 and U31 (Bustard Head). This is normally not a significant mud scallop area. They are mainly caught much further north near Hydrographers Passage (~21° S) outside the scallop fishery assessment domain.

For this stock assessment, the catch for the closed months recorded in the logbook data was included in the harvest data for model input. This means that the assumption is that they were saucer scallops that were illegally being reported as mud scallops. If there is a genuine, recent move by industry to target and record mud scallop catch in closed months, then the definition of scallop catch for future assessments needs to be altered.

6.2 Natural mortality

Concerns over the traditional estimate of natural mortality M from Dredge (1985) were:

- All recaptured scallops in the study of Dredge (1985) were obtained by the fleet during their normal commercial fishing activities. This would mean the tagged scallop population was declining as a result of both natural mortality M and fishing mortality F acting simultaneously. These combined mortality rates are referred to as total mortality Z (i.e. $Z=M+F$) and in such studies it is very difficult to separate and quantify the individual mortality rate components. The estimate of M would have been confounded by the fishing mortality F.
- There was some additional fishing mortality in the study of Dredge (1985) attributed to non-reporting of recaptured tagged scallops which is not taken into account in the study. The estimate of M would have been confounded by this additional fishing mortality.

To improve on the previous estimates of mortality, Courtney et al. (2020) conducted tag-recapture experiment conducted inside two closed SRAs in 2018 and 2019. Three statistical methods were applied to the tagging data based on 1) the Brownie et al. (1985) model, 2) a modified version of the Brownie model and 3) a binomial logistic regression model of recaptures.

The logistic model incorporated the following influential factors and terms:

- Lunar phase
- SRA (2 levels, HBA and YB)
- Scallop size class at tagging (3 levels; small <90 mm shell height (SH), medium 90–95 mm SH and large >95 mm SH)
- Average number of days-at-liberty for each batch of recaptured scallops was included as a continuous variable
- Interaction between days-at-liberty and SRA was also included in the model

6.3 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 2019 stock assessment.

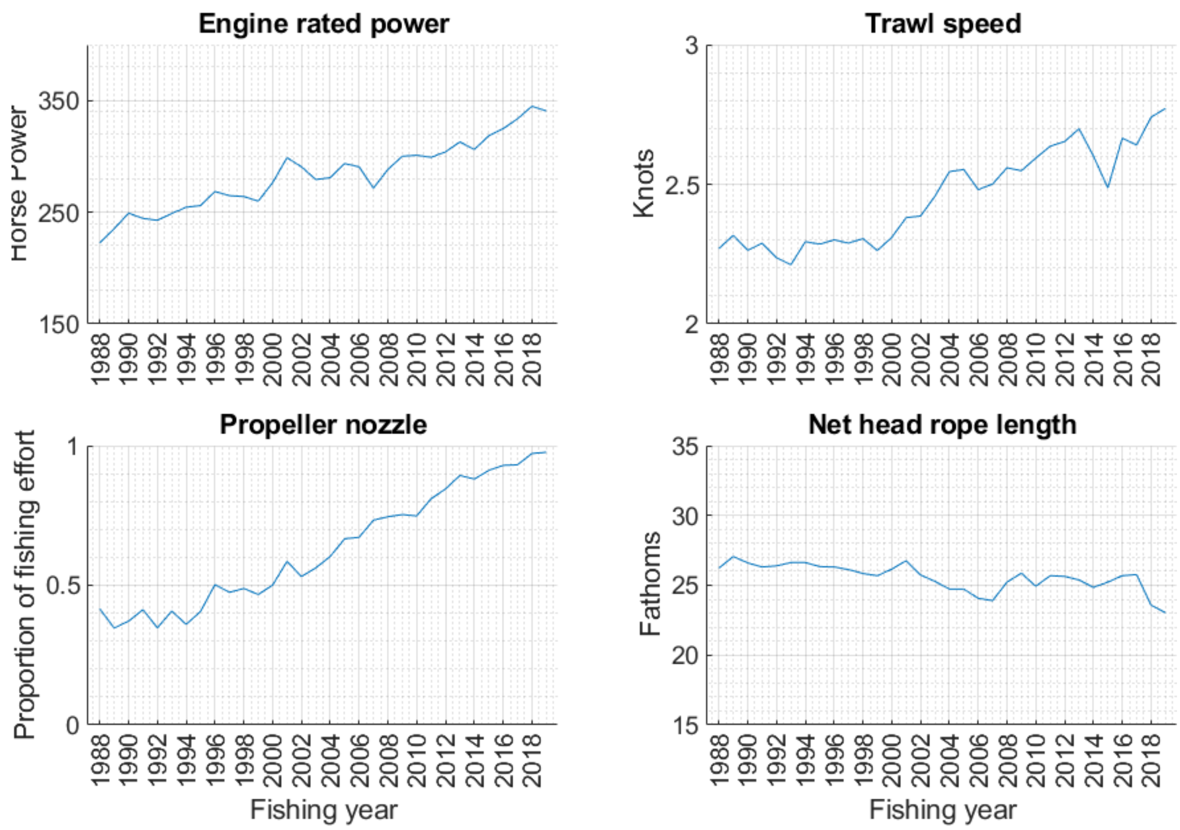

Figure 15 The scallop-fleet average engine rated power, trawling speed, use of propeller nozzles and net size by fishing year. Averages were weighted according to the number of days fished by each vessel in each fishing year

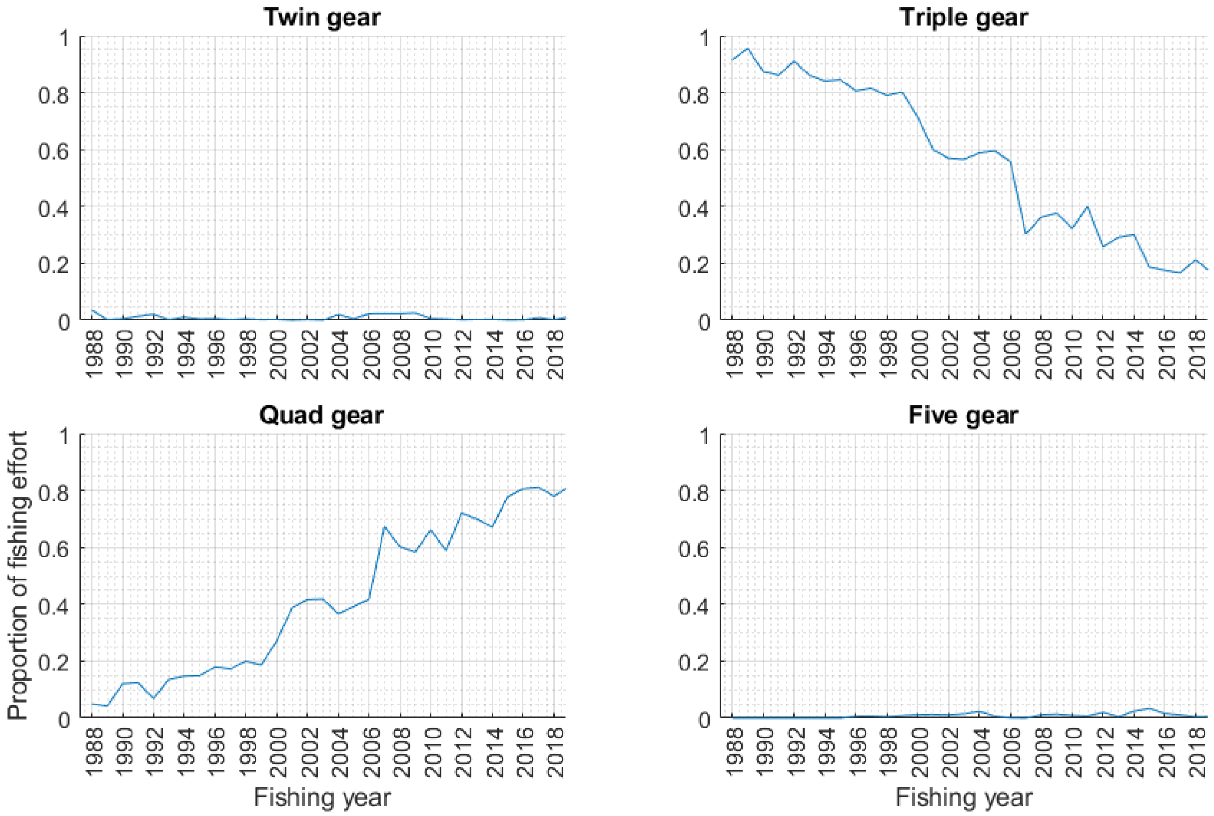

Figure 16 The proportion of total annual fishing effort by vessels using the net configuration

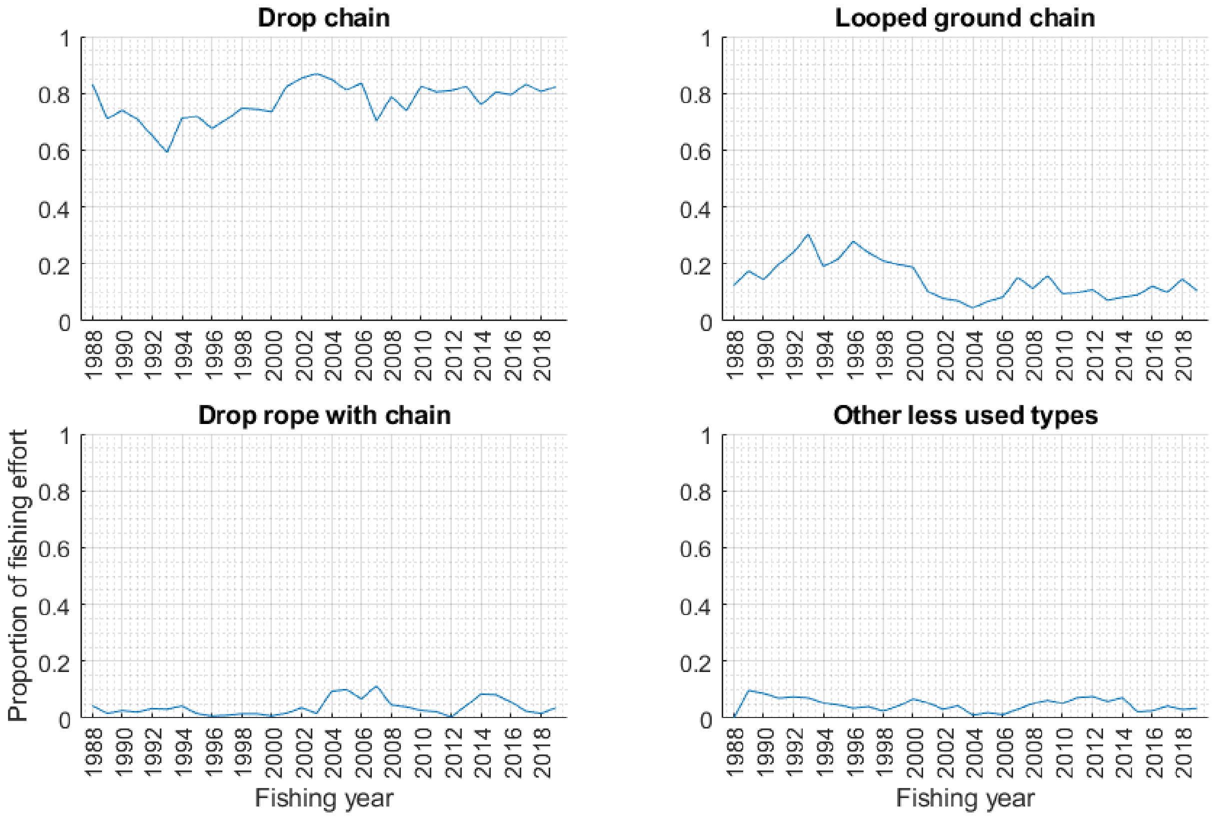

Figure 17 The proportion of total annual fishing effort by vessels using the ground gear configuration

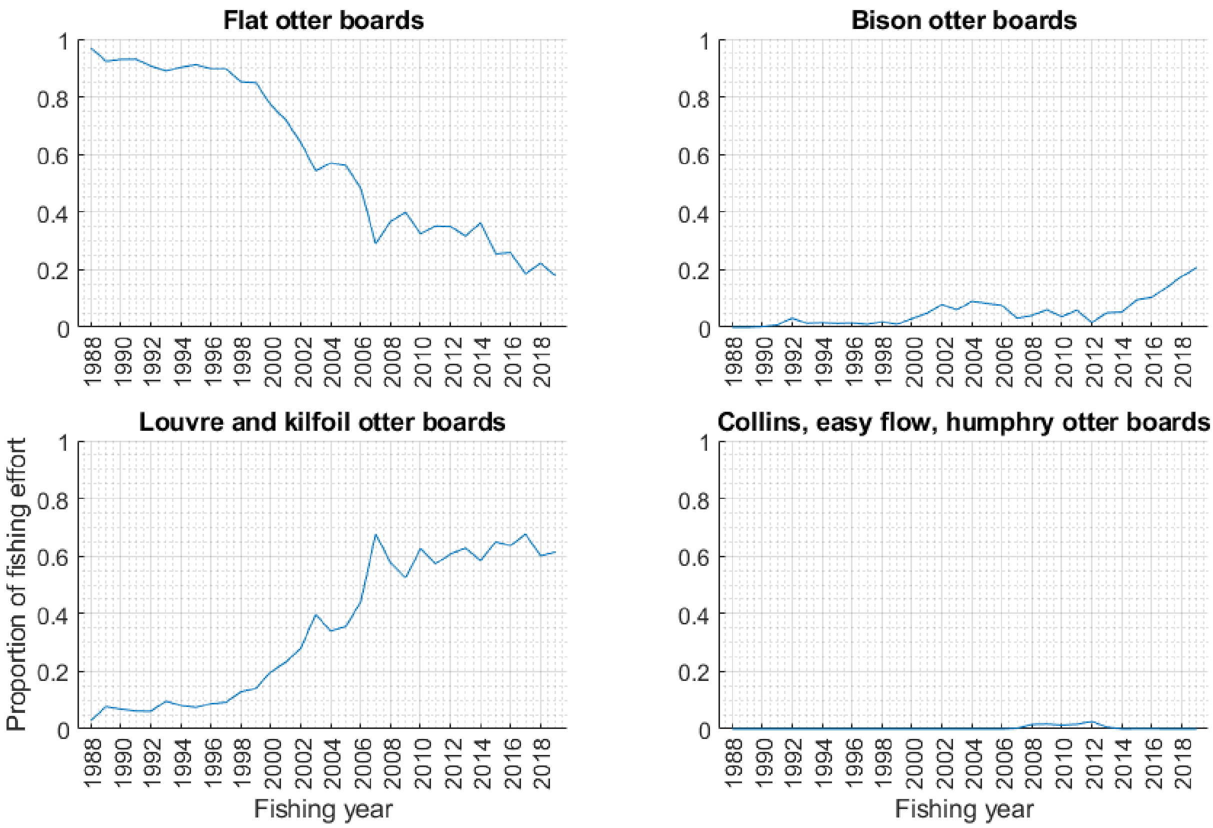

Figure 18 The proportion of total annual fishing effort by vessels using the otter board configuration

6.4 Fishing power

The 1988–2018 catch rate standardisation measured annual changes in fishing power, based on fixed and random model components (O'Neill and Leigh 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 19, where fishing power increased by about 15% from 1989–2019. 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 20% from 1989–2019. The drop in fishing power from 2018–2019 is likely due to better boats leaving the scallop fishery.

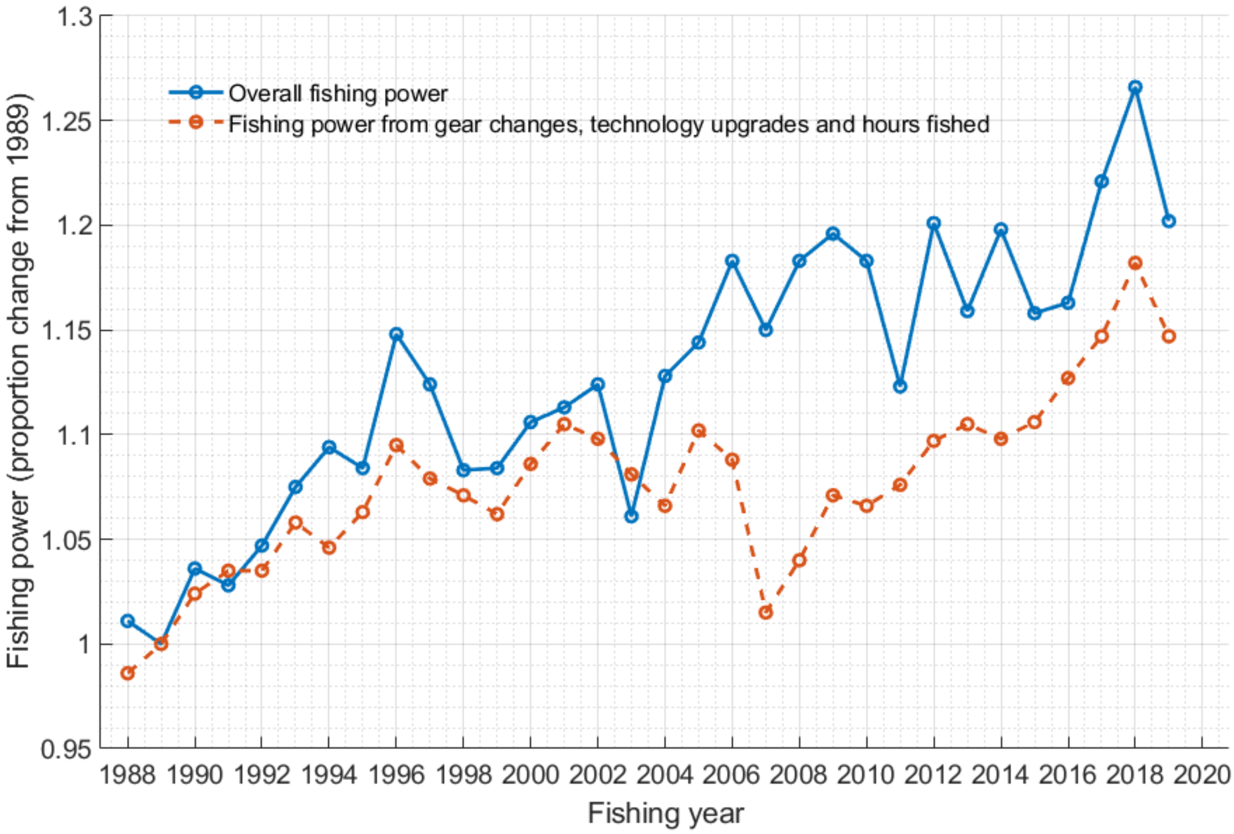

Figure 19 Annual fleet fishing power on saucer scallops, as calculated from the REML model. The changes represent the difference from year 1989, which was set to one

6.5 Population model

Table 7 Equations for the age-based population dynamics for region 3

Aged-Based Population Dynamics	
Notations to represent time and scallop age	**Equation**
• Fishing year $\boldsymbol{y}$ started from 1956 and finished in 2019. Fishing year $\boldsymbol{y}$ was defined as a time interval starting from November of calendar year $\boldsymbol{y}$-1 to October of calendar year $\boldsymbol{y}$. • Population dynamics were presented in monthly time steps $\boldsymbol{t}$ from 1 to 768 (i.e. 12 months × 64 fishing years.) • Scallop ages were stratified into 48 months denoted by $\boldsymbol{a}$=1,...,48. Saucer scallops were assumed to live for up to four years of age.	
Number of Scallops N_{ta}:	
The number of scallops $\boldsymbol{N_{ta}}$ at age $\boldsymbol{a}$ at monthly time-step $\boldsymbol{t}$ was modelled with the following recursive equation, $\boldsymbol{N_{ta}} = \begin{cases} \boldsymbol{R_t} & \text{for } \boldsymbol{a} = \mathbf{1} \\ \boldsymbol{N_{t-1,a-1}} \exp\left(-\boldsymbol{Z_{t-1,a-1}}\right) & \text{for } \boldsymbol{a} = \mathbf{2}, \ldots, \mathbf{48} \end{cases}.$ Note that $\boldsymbol{N_{ta}}$ represented the number of scallops at the beginning of time-step $\boldsymbol{t}$; in addition, it also represented the number of scallops at the end of time-step $\boldsymbol{t-1}$.	(1)
Recruitment number R_t:	
The number of scallops recruited $\boldsymbol{R_t}$ at age group $\boldsymbol{a}$=1 at time-step $\boldsymbol{t}$ was defined as follows, $\boldsymbol{R_t} = \frac{\boldsymbol{E_{y-1}}}{(\boldsymbol{\alpha_k} + \boldsymbol{\beta_k E_{y-1}})} \exp(\boldsymbol{\eta_y})\, \boldsymbol{\phi_t},$ where $\boldsymbol{\eta_y}$ was annual recruitment deviation of fishing year $\boldsymbol{y}$. Besides, assume $\boldsymbol{\eta_y} = \mathbf{0}$ for $\boldsymbol{y} = \mathbf{1956}, \ldots, \mathbf{1987}$.	(2)
Annual number of eggs E_y:	
The number of eggs $\boldsymbol{E_y}$ produced in fishing year $\boldsymbol{y}$ was defined by the relation, $\boldsymbol{E_y} = \mathbf{0.5} \sum_t \sum_a \boldsymbol{N_{ta}} \times \mathrm{Mat}_a \times \mathrm{Fec}_a \times \mathrm{Spawn}_t.$ • Mat_a was the proportion of scallop mature at age $\boldsymbol{a}$. • Fec_a was the number of eggs produced by a scallop at age $\boldsymbol{a}$. • Spawn_t was the 12 month spawning pattern, defining proportion of annual egg production produced at time-step $\boldsymbol{t}$. It was important to note that the sum of Spawn_t over the 12 fishing months of fishing year $\boldsymbol{y}$ was equal to 1. • The value 0.5 represented the assumption that half of $\boldsymbol{N_{ta}}$ were females.	(3)
Recruitment pattern ϕ_t:	
For each fishing month $\boldsymbol{t}$, within each fishing year, the proportion of recruitment was modelled as follows, $\boldsymbol{\phi_t} = \exp(\boldsymbol{\kappa} \cos(2\boldsymbol{\pi}(\boldsymbol{m_t} - \boldsymbol{\theta})/\mathbf{12})) / \sum_{m_{t'}=1}^{12} \exp\left(\boldsymbol{\kappa} \cos\left(2\boldsymbol{\pi}(\boldsymbol{m_{t'}} - \boldsymbol{\theta})\right)\right),$ where $\boldsymbol{m_t}$ was the fishing month at time-step $\boldsymbol{t}$ in fishing year $\boldsymbol{y}$ and ranged from 1 (i.e. November) to 12 (i.e. October). For each fishing year, the sum over 12 months was equal to $\sum_t \boldsymbol{\phi_t} = \mathbf{1}$. Notice that equation (4) 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.	(4)
Survival rate $\exp(-\boldsymbol{Z_{ta}})$:	
Survival rate $\exp(-\boldsymbol{Z_{ta}})$ at age $\boldsymbol{a}$ at monthly time-step $\boldsymbol{t}$ was the product of the survival rates from natural mortality $\boldsymbol{M}$ and harvest rates $\boldsymbol{u_t}$. The mathematical expression was written with the following form $\exp(-\boldsymbol{Z_{ta}}) = \exp(-\boldsymbol{M})(\mathbf{1} - \boldsymbol{v_{ta} u_t}).$ The equation factors represented survival rates from natural mortality and fishing, respectively.	(5)
Harvest rate u_t:	
$\boldsymbol{u_t} = \boldsymbol{C_t}/(\boldsymbol{B_t^{(1)} b_t^{-1}}),$ where $\boldsymbol{C_t}$ represented the total harvest (in baskets) at time-step $\boldsymbol{t}$, and $\boldsymbol{b_t}$ was the converter for basket and meat weight.	(6)
Midmonth exploitable biomasses—forms $B_t^{(1)}$ and $B_t^{(2)}$:	

$B_t^{(1)} = \sum_a N_{ta} w_a v_{ta}^* \exp(-0.5M\ \ ),$ (7)

$B_t^{(2)} = \sum_a N_{ta} w_a v_{ta}^* \exp(-0.5M\ \ )\sqrt{1-u_t}.$ (8)

Note that $B_t^{(1)}$ 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 large than C_t. $B_t^{(2)}$ was used to connect catch rates. Use of equation $B_t^{(1)}$ with fixed 2018 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 $G_t(\ell, \mathrm{MLS}_t)$ 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 (see Equations (7) and (8)) and v_{ta} used for survival rate of Equation (5). Both of v_{ta} and v_{ta}^* were written as

$v_{ta} = \int_\ell f_a(\ell) v_t(\ell)\left(G_t(\ell, \mathrm{MLS}_t) + (1 - G_t(\ell, \mathrm{MLS}_t))d_t\right)d\ell,$ (9)

$v_{ta}^* = \int_\ell f_a(\ell) v_t(\ell) G_t(\ell, \mathrm{MLS}_t) d\ell.$ (10)

Specifically, for the period prior to 1981, there was no minimum legal size, and $v_{ta} = v_{ta}^*$, that is, $v_{ta} = v_{ta}^* = \int_\ell f_a(\ell) v_t(\ell) d\ell$.

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

$c_t^{(f)} = q_t B_t^{(2)} b_t^{-1},$ (11)

$c_t^{(s_{0+})} = \dfrac{q^{(s_{0+})}\left(\sum_{a=1}^{48} N_{ta} \exp(-0.5M\ \ ) P_a(\ell \le 78\text{mm})\right)}{A},$ (12)

$c_t^{(s_{1+})} = \dfrac{q^{(s_{1+})}\left(\sum_{a=1}^{48} N_{ta} \exp(-0.5M\ \ ) P_a(\ell > 78\text{mm})\right)}{A},$ (13)

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, and two other values 0.2 and 0.4 were sensitivities (Miller et al. 2019; Joll and Penn 1990).

Table 8 Population model parameters and definitions

Model parameters		
Known	**Equations and values**	**Notes**
$\boldsymbol{\ell_a}$	$\ell_a = 104.587(1 - \exp(-0.159a))$	Shell height (length mm) at age a. The estimate of standard deviation of the error term was 2.285 mm (Campbell, Officer, et al. 2010).
$\boldsymbol{f_a(\ell)}$	The normal probability density of length at age a, with mean ℓ_a and variance 2.285^2.	
$\boldsymbol{P_a(\ell \leq L)}$	$\int_0^L f_a(\ell)d\ell$	The probability of length less than or equal to L at age a.
$\textbf{Mat}_\ell$	$\text{Mat}_\ell = \dfrac{\exp(-8.72 + 0.1085\ell)}{1 + \exp(-8.72 + 0.1085\ell)}$	Proportion mature at length l, estimated on Dredge (1981) data. For the data, the maturity asymptote was less than one.
$\textbf{Mat}_a$	$E_a(\text{Mat}_\ell) = \int f_a(\ell)\text{Mat}_\ell d\ell$	Proportion mature at age a, based on Mat_ℓ and $\ell_a \sim N(\ell_a, 2.285^2)$.
$\textbf{Fec}_a$	$\zeta_a = 3220.708\ell_a^{1.354}$	Fecundity of shell height at age a (Dredge 1981; O'Neill et al. 2005), used in Equation (3) to produce annual number of eggs.
$\textbf{Spawn}_t$	0.0072 $t \in$ November 0.0000 $t \in$ December 0.0144 $t \in$ January 0.0288 $t \in$ February 0.0899 $t \in$ March 0.1331 $t \in$ April 0.1403 $t \in$ May 0.1439 $t \in$ June 0.1439 $t \in$ July, 0.1403 $t \in$ August, 0.0863 $t \in$ September, 0.0719 $t \in$ October.	Monthly spawning pattern (Dredge 1981; O'Neill et al. 2005), used in Equation (3) to produce annual number of eggs.
$\boldsymbol{w_a}$	$w_a = 1.259 \times 10^{-9}\ell_a^{3.485}$	Meat weight (kg) at age a (O'Neill et al. 2005), used in Equation (7) and (8).
$\boldsymbol{b_t}$	6.5 $t \in$ November 7 $t \in$ December 7 $t \in$ January 7.5 $t \in$ February 7 $t \in$ March 6.5 $t \in$ April 6 $t \in$ May 5 $t \in$ June 5 $t \in$ July, 5 $t \in$ August, 5.5 $t \in$ September, 6 $t \in$ October.	Baskets to meat-weight conversion (kg per basket) (O'Sullivan et al. 2005), used in Equation (6) and (10).
$\boldsymbol{v_t(\ell)}$	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, Officer, 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.
$\boldsymbol{G(\ell, \textbf{MLS}_t)}$	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.	Probability of retention by a tumbler (Campbell, Officer, et al. 2010). Tumbler use was sporadic in the 1970s, but was utilised from late 1980.

		○ 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.	
$\boldsymbol{d}$	3.3%		Discard mortality (Campbell, Officer, et al. 2010).
$\boldsymbol{A}$	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			
$\boldsymbol{R_0}$ **and** $\boldsymbol{h}$	$\alpha_k = E_0(1-h)/(4hR_0)$, $\beta_k = (5h-1)/(4h)$, $R_{0,k} = \exp(\gamma\ \ ) \times 10^9$, $h = \frac{1+\exp(\xi)}{5+\exp(\xi)}$.		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].
$\boldsymbol{\kappa}$ **and** $\boldsymbol{\theta}$			θ and κ were parameters of centre location and concentration of Equation (4).
exp $(-\boldsymbol{M}\ \ )$	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).
$\boldsymbol{q_t}$	Scallop catchability composed of three components with the form: $\exp\left(\gamma_q\ \ + \gamma_{\text{jan}}\delta_t + \gamma_s \cos\left(\frac{2\pi t}{12}\right)\right) \times 10^{-7}$, 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.
$\boldsymbol{q^{(s_{0+})}}$	$q^{(s_{0+})} = \exp\left(\gamma_{q^{(s_{0+})}}\right)$,		Catchability of 0+ scallop.

Table 9 The negative log-likelihood functions for the model

-LL functions

Fishery log standardised catch rates or log survey densities:

$$\boldsymbol{l} = \frac{n}{2}\left(\log(2\pi) + 2\log(\sigma) + (\hat{\sigma}/\sigma)^2\right),$$

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, $\hat{\sigma} = \sqrt{\sum\left(\log(c) - \log(\hat{c})\right)^2 / n - 1}$, and n was the number of monthly data.

***h steepness*:**

$$l_h = \begin{cases} 0.5\left(\frac{\xi - \log(19)}{1.2}\right)^2, \text{if } \xi > \log(19) \\ 0.5\left(\frac{\xi - \log(19)}{1.2 * 0.3333}\right)^2, \text{if } \xi < 0 \end{cases}$$ **(O'Neill and Buckley 2018)**

θ:

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

κ:

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

***harvest rate u*:**

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

Log recruitment deviations η_y *for* $y = 1988, \ldots, 2018$:

$$nssRec = 2018 - 1988$$

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

$$sigmaR = \min\left(\max(sigmaRhat, 0.1), 0.2\right)$$

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

Recruitment parameters to ensure log deviations sum to zero with standard deviation. $\eta = \zeta e$, 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;
```

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

7 Appendix B: Model outputs

7.1 Catch rate diagnostics

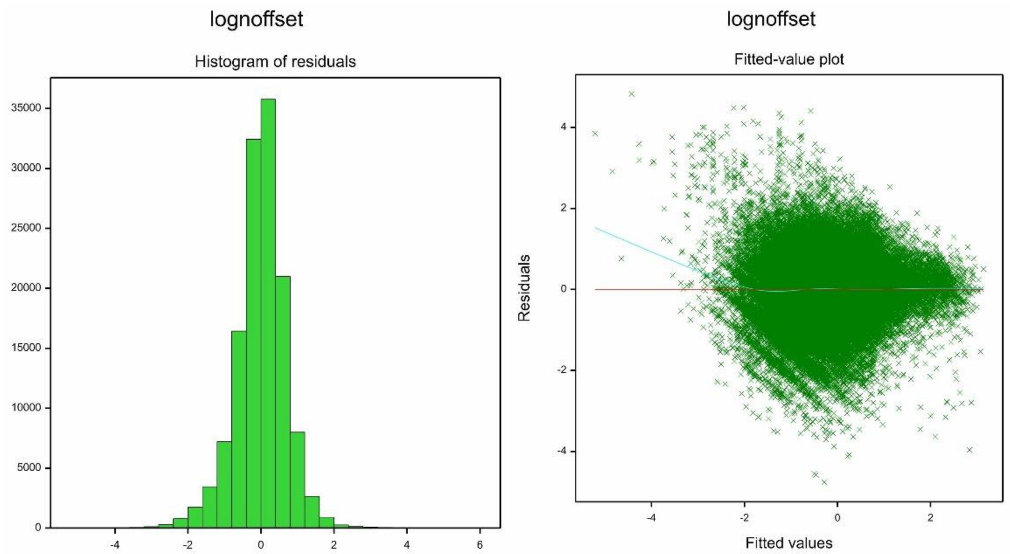

Figure 20 Standardised residuals for the scallop catch rate analysis 1977–2019

7.2 Model fit

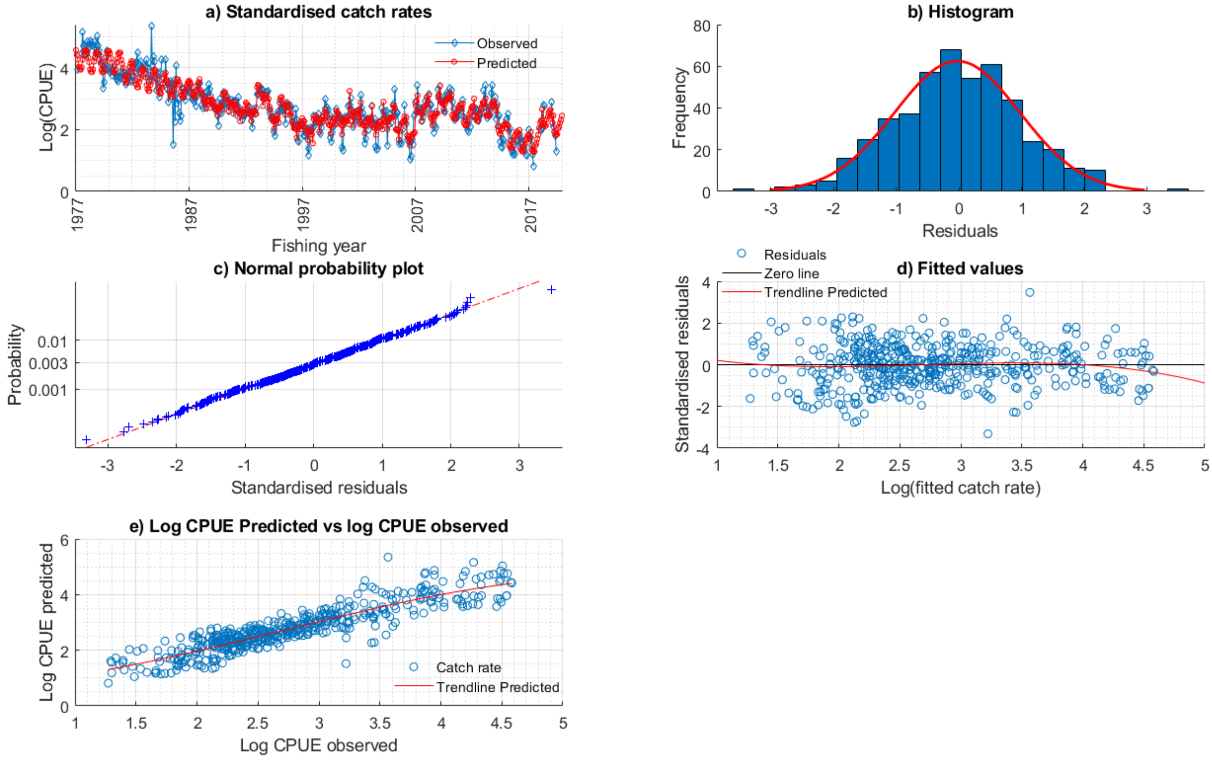

Figure 21 Catch rate fit-diagnostics

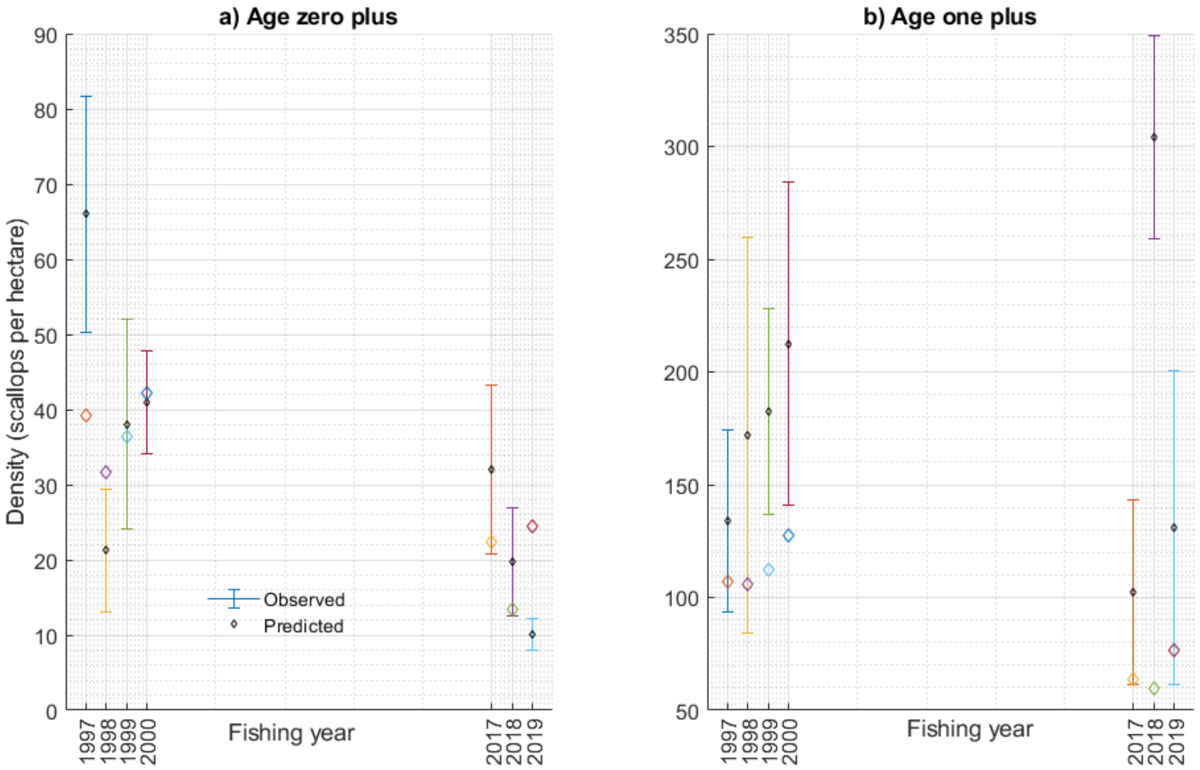

Figure 22 Age 0+ and 1+ densities from the model. The error bars depict ± one standard error

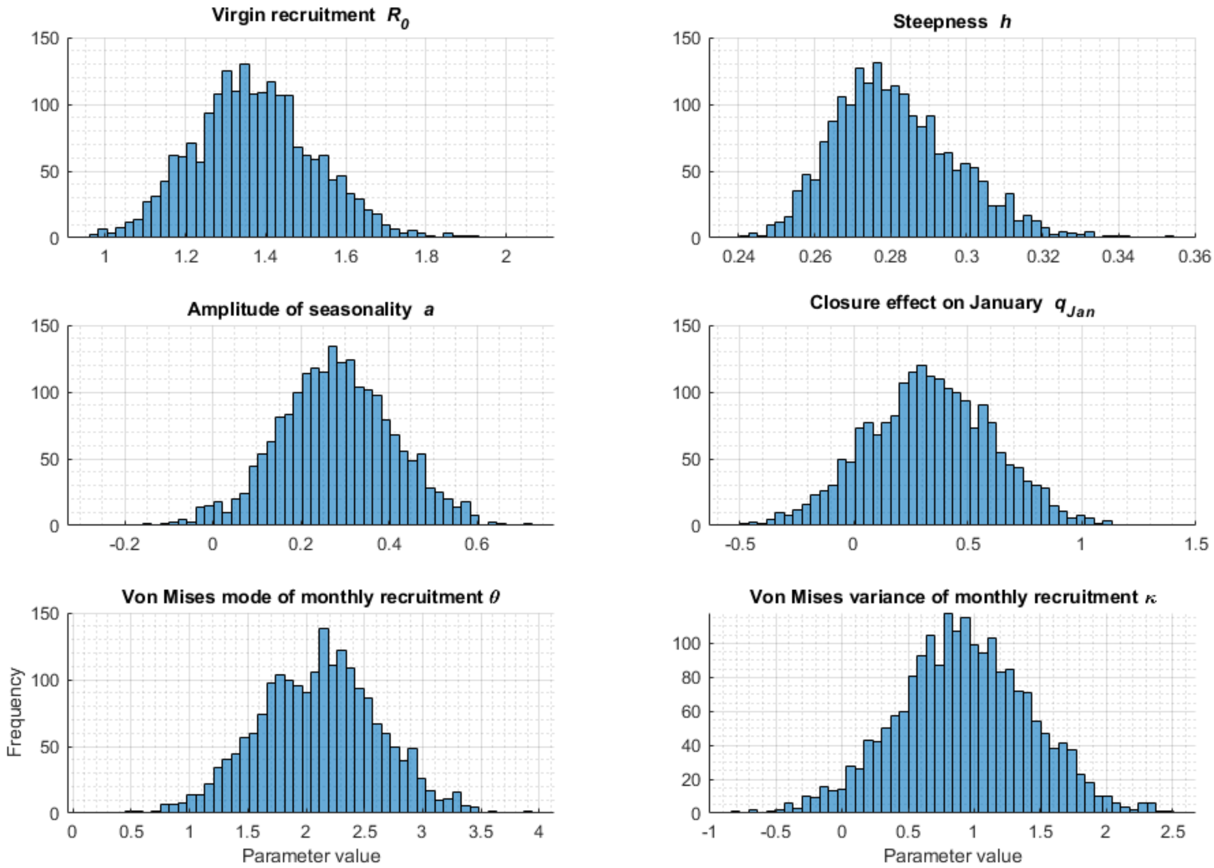

Figure 23 MCMC parameter estimates for the six main parameters from the model. n = 1000 samples, thinned from 200 000 iterations of each parameter

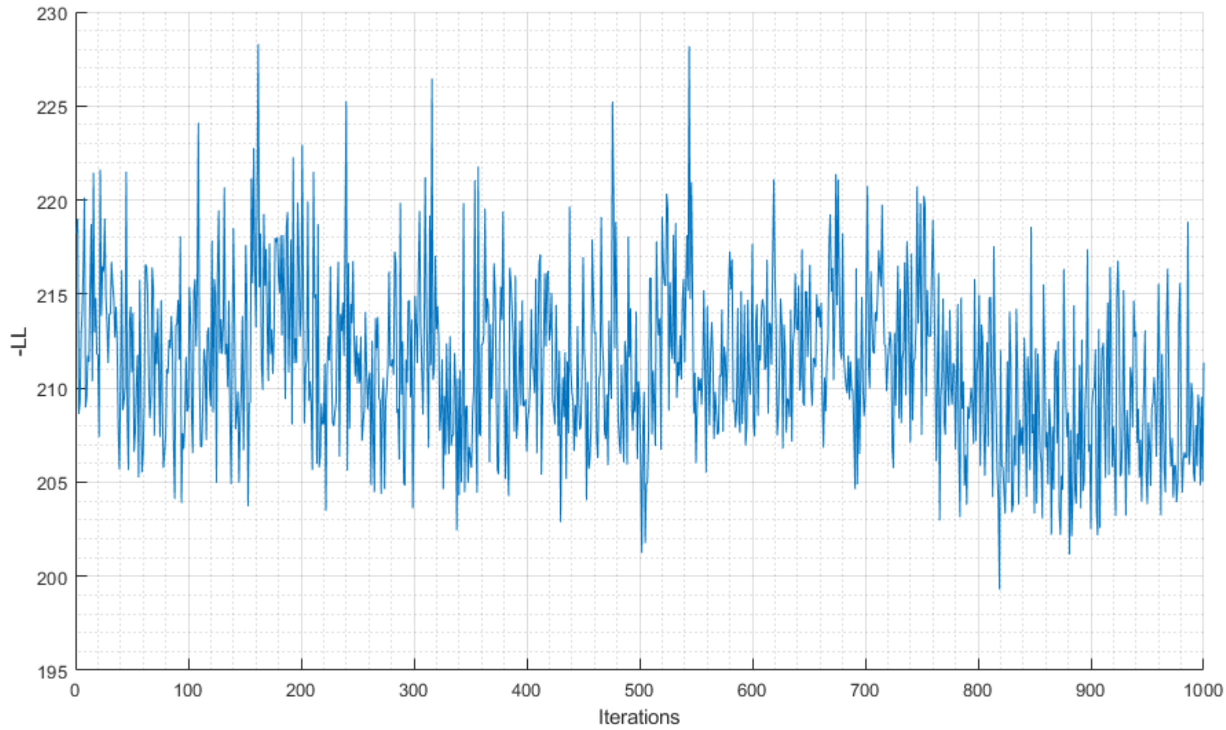

Figure 24 MCMC –LL trace for the model with n = 1000 samples, thinned from 200 000 iterations of each parameter

Table 10 Parameter estimates for the six main parameters from the median MCMC parameters with n = 1000, thinned from 200 000 iterations for each parameter

Parameter	Estimated value (s.e.)
Virgin recruitment R_0	1.3602×10^9 (0.0389×10^9)
Steepness *h*	0.2796 (0.0060)
Amplitude of seasonality *a*	0.2762 (0.0681)
Closure effect on January q_{Jan}	0.3352 (0.1506)
Von Mises mode of monthly recruitment θ	2.0769 (0.5524)
Von Mises variance of monthly recruitment κ	0.8954 (0.2653)