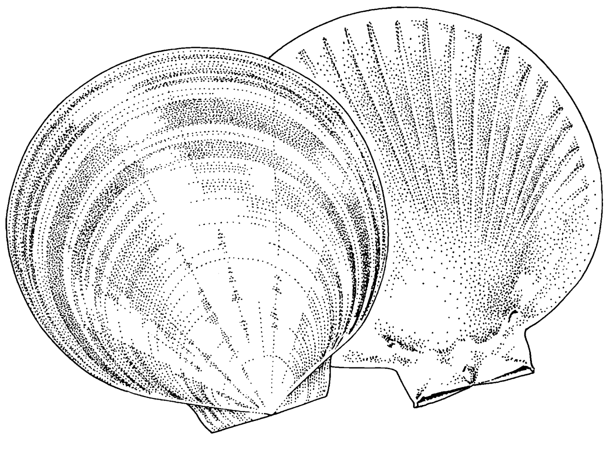
Stock predictions and population indicators for Australia's east coast saucer scallop fishery



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- Fisheries Queensland – Eddie Jebreen, Darren Roy, Daniel McInnes.
- Great Barrier Reef Maine Park Authority – Rachel Pears.
- Department of Environment and Heritage Protection – Maria Zann.
- Western Australian Department of Fisheries – Nick Caputi and Mervi Kangas.
- James Cook University – James Daniell.
- Australian Ocean King Prawn Company – Stephen Murphy.
- Urangan Fisheries – Nick Schulz.
- Fishers – Andrew Redfearn, and Kevin Reibel.

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Glossary

ADMB	AD Model Builder, a statistical application
BH	Bustard Head, a scallop fishery zone.
BHA	Scallop replenishment area A within Bustard Head.
BHB	Scallop replenishment area B within Bustard Head.
BRD	Bycatch reduction device.
B	Exploitable biomass: the combined weight of legal sized scallop.
B_0	Mean equilibrium virgin exploitable biomass: average biomass level before fishing.
B_{20}	Exploitable biomass equal to 20% of B_0. This is a limit reference point.
B_{40}	Exploitable biomass equal to 40% of B_0.
B_{50}	Exploitable biomass equal to 50% of B_0.
B_{60}	Exploitable biomass equal to 60% of B_0. This is a potential target reference point B_{TARG} within the Sustainable Fisheries Strategy.
B_{MSY}	The exploitable biomass that can support a potential harvest of maximum sustainable yield.
B_y	Exploitable biomass in fishing year y. For example, B_{2018}.
Catch rate	Index of scallop abundance, referred to as the average catch-rate standardised to a constant vessel, fishing power and fishing effort through time.
CFISH	The Queensland commercial fishery logbook database.
Chl-a	Chlorophyll-a concentration.
DAF	Department of Agriculture and Fisheries.
ERSSTv5	Extended Reconstructed Sea Surface Temperature v5 – a global monthly dataset for sea surface temperature.
E_y or S_y	Number of eggs (egg production) in fishing year y. The biomass reference-point terminology, like E_0 or E_{MSY}, also applies.
eu	Effort units = standardised boat-days × standardised hull units.
F_{B40}	Harvest rate for equilibrium exploitable biomass equal to 40% of B_0.
F_{B50}	Harvest rate for equilibrium exploitable biomass equal to 50% of B_0.
F_{MSY}	Harvest rate for equilibrium MSY.
F_{B60}	Harvest rate for equilibrium exploitable biomass equal to 60% of B_0.
Fishing year	Fishing year y was from November until October the following year. For example, fishing year label 2018 was from November 2017 to October 2018, where November was fishing month 1 and October was fishing month 12.

FI	K’gari, Fraser Island.
FQ	Fisheries Queensland.
GLM	Generalised linear model.
GBRMP	Great Barrier Reef Marine Park
Harvest	Number or weight of scallop caught and retained.
HB	Hervey Bay, a scallop fishery zone.
HBA	Scallop replenishment area A within Hervey Bay.
HBB	Scallop replenishment area B within Hervey Bay.
HTrawl	Voluntary daily trawl logbook records of prawn and scallop catch rates prior to 1988.
LMM	Linear mixed model used 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, an American scientific agency.
Non-spatial	The zone-combined (region 3) stock model analysis through MATLAB.
OISST	Optimum Interpolation Sea Surface Temperature.
RAP	Representative Areas Program.
RBC	Recommended biological catch.
Region 3	The scallop fishery for the main fishing areas of Yeppoon, Bustard Head and Hervey Bay, and excludes the K’gari zone.
REML	Restricted maximum likelihood, an estimation method in linear mixed models.
RSE	Relative standard error, which is the standard error divided by the mean.
R_0	Mean equilibrium virgin recruitment: average recruitment level before fishing.
Spatial-M1	Ten-area ADMB stock model analysis.
Spatial-M2	Ten-area MATLAB stock model analysis.
SRA	Scallop replenishment area.
SST	Sea surface temperature.
t	Tonnes.
TED	Turtle exclusion device.

TrackMapper	Software to join and spatially analyse VMS and CFISH logbook data.
VMS	Vessel monitoring system, high spatial resolution satellite coordinates.
Y	Yeppoon, a scallop fishery zone.
YA	Scallop replenishment area A within Yeppoon.
YB	Scallop replenishment area B within Yeppoon.

Executive Summary

What is the report about?

This project undertook urgent analyses to understand the roles of overfishing and the environment on saucer scallops.

Results of this study indicated a continual decline in numbers of spawning scallops. High levels of fishing effort since the 1980s contributed to stock depletion. In addition, environmental influences such as increased sea surface temperatures (SST) may have amplified scallop mortality rates.

These findings can be applied to efforts for stock rehabilitation for the scallop fishery between Yeppoon and K'gari (Fraser Island). Recommended management actions include reduction of the spatial intensity of fishing effort applied, and ensuring sufficient annual spawning to support the scallop population and fishery.

Background

The saucer scallop fishery was once Queensland's most valuable commercial species. Annual landings (adductor muscle meat-weight) peaked near 2000 tonnes (t) in 1993 and were valued near AUD$30 million. In recent years, fishery productivity and performance declined. The scallop harvest of 175 t in the 2016 fishing-year was the lowest on record since 1988. There has been concern among fishery managers, scientists, fishers and other stakeholders over this decline.

These concerns prompted the Queensland Department of Agriculture and Fisheries to undertake a stock assessment of saucer scallops in mid-2016. Findings showed that standardised catch rates were the lowest on record, signifying a spawning stock ≤ the low catch rates 20% of early 1977 estimates. As a result, scallops were classified as overfished.

Although it was clear that fishing practices had impacted scallop abundance, the role of environmental factors was less clear. In the absence of necessary data to drive informed management of harvest controls, a series of closure were introduced to prevent further stock declines.

There is now a need to understand the respective roles of fishing effort and environmental drivers on scallop abundance. There is also a need for new management procedures that are appropriate given the present poor status of the scallop population.

Objectives

1. Design stock model structures and estimate associations between saucer scallop abundance and environmental variables.
2. Improve indicators and stock model predictions to estimate the current population size of saucer scallops for management procedures.

Methodology

A series of linear regressions were applied to correlate November–January catch rates with environmental influences both spatially and temporally. The study design included two environmental variables: chlorophyll-a concentration (Chl-a) and sea surface temperature (SST).

Fishery area mapping was combined with surveyed scallop densities to produce estimates of scallop population size. Scallop densities (i.e. the number of scallops per hectare) were determined using spatial statistical methods (geo-statistical kriging) for ten areas.

Age-based population dynamic models were built, and included sea surface temperature, and scallop biological, harvest, catch rate, and density-area data. The models were used to predict spawning levels as indicators of scallop abundance for the whole fishery. They also used to provide reference points or simple projections (forecasts) for fishery management options.

The stock models examined scallop data on a monthly basis for the fishing years 1956 to 2018. The models represented the processes of scallop births, growth, reproduction and mortality using every month age classes from one to 48 months (4-year life cycle). Ten areas covering four large zones and six scallop replenishment areas (SRAs) within the three larger zones of Yeppoon, Bustard Head and Hervey Bay were modelled.

As statistical errors can be expected to increase with spatially split data, a simple validation can be performed by running a simpler non-spatial model by which results may be compared.

Results/key findings

Above average winter SST was negatively associated with scallop survival, abundance, and catch rates during the next seasons, despite that the scale of increase in sea surface temperatures (SST anomalies) over the years studied was not large (up to one degree Celsius). Queensland scallops have not endured high sea surface temperature anomalies like those experience in Western Australia 202010/11, which were recorded as high as 2–4 °C. Chlorophyll associations were inconsistent.

Results showed significant effects of rising winter SST on natural mortality. For the range of SST anomalies, 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 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.

Modelled estimates for spawning biomass (egg production) with elevated SST in 2018 were less than 20 per cent of 1956 levels. This result, in the context of future fishery management and harvest strategies, suggested harvest/effort control rules should incorporate the higher natural mortality that could occur with elevated SSTs. This is an important consideration, given that many years in the last two decades experienced above average winter SSTs.

The results from the simpler non-spatial model, excluding SST, suggested the spawning biomass in region 3 (Figure 3, page 3) in 2018 was at 22 per cent (95 per cent confidence interval 17–32 per cent) of the virgin (unfished) level in 1956.

Model results indicate that the scallop spawning population size was less than the spawning level required for maximum sustainable yield (MSY) at 45 per cent. Across analyses, results revealed broader uncertainty between models, having different structural setups, data and assumptions. When the greater uncertainty is considered, the results suggested the 2018 spawning biomass was below 30–40 percent of virgin levels in 1956, with a midpoint of 15–20 per cent.

For 2018, results suggested up to 160 t of scallop meat was a sustainable maximum take from region 3. After heavy fishing, minimal stock appeared to be present in October 2018 off K'gari (Fraser Island). The non-spatial model presented in this study projected that trawling be limited to approximately 60 000 effort units in order to promote a higher biomass, which is one of the ecological objectives of the Queensland Government's Sustainable Fisheries Strategy 2017–2027. The effort units equate to about 1100 fishing days, scaled to the modern fishing power of the fleet.

The dramatic size of difference between forecasts with and without SST was grounds to treat the effects of rising sea surface temperature carefully.

The spawning biomass results of the 2018 stock assessment were marginally higher than the 2016 stock assessment. This was likely a result of fishery management changes in 2017.

Further minor work is required to strengthen and select a modelling method for regular stock assessment. The non-spatial model is recommended for ease and consistency. However, before using in management procedures, the present model needs to demonstrate valid inferences that match the pending new estimate of natural mortality from the FRDC project 2017-048.

Table 1. Summary results for region 3, including Yeppoon, Bustard Head and Hervey Bay.

Indicator	**Result**
Current spawning biomass / unfished biomass	22 per cent
Maximum sustainable yield (MSY) spawning biomass / unfished biomass	45 per cent
Potential MSY (tonnes meat / year) at MSY biomass	363–499 t
Potential MSY harvest from the 2018 biomass	161 t
Current harvest (tonnes meat in 2018)	166 t
Harvest proportions	All commercial trawl
Potential harvest at 60 percent biomass (B_{60})	333–448 t
Trawl effort units to build to B_{60}	< 60 000
Time to build to B_{60}	10–20 years

Implications for relevant stakeholders

1. Outputs of the project will inform new management procedures under the Queensland Government's Sustainable Fisheries Strategy. Fishers may need to operate under new rules. Use of the scientific advice herein may result in a doubling of current fishery yields from below 200 t to near 400 t in future (≥10) years. Use of results may help achieve higher catch rates, stabilise the fishery at higher profit levels, and improve fishery sustainability and supply to domestic and overseas markets.
2. Industry to be aware that elevated sea surface temperatures may reduce scallop spawn survival, catch rates, landings and profits. Monitoring of sea temperatures and forecasts may help plan annual fishing investment.
3. Short-term model forecasts (< 10 years) indicate that a return to levels of harvest greater than 400 t are unlikely to occur. Processors and fishers need to consider the results in their business plans.

Recommendations

1. Revise fishery management to better control fishing effort, to help increase scallop biomass.
2. Update estimates of natural mortality and growth, using all historical tagging data and new data from FRDC 2017-048.
3. Continue annual fishery independent abundance surveys of scallops to validate stock status and to optimise management procedures. The abundance of scallops aged 1+ years during winter was the critical index for measuring spawning biomass (that is the potential egg production).
4. Surveys need to calculate their catching efficiency, with measures of effective trawl swept area, and the percentage of scallops caught per sweep.
5. Monitor, assess and report on sea surface temperature/ocean anomalies, and consider forecasts in management discussions. Use of site-specific sea-floor water temperature sensors may provide better data.
6. Review the time-series data on trawl fishing power through compulsory logbook gear sheets.
7. Continue to evaluate and improve the time series of standardised catch rates.
8. Continue to adjust data and models, to improve estimates and forecasting, and accuracy of reference points.

Keywords

Saucer scallop, *Ylistrum balloti*, *Amusium balloti*, indicators, reference points, management, stock assessment, sea surface temperatures, population dynamics

1 Introduction

1.1 Background and need

The Australian east coast saucer scallop (*Ylistrum balloti*, formerly *Amusium balloti*) fishery used to be Queensland's most valuable commercially fished species. Annual landings peaked near 2000 t (adductor muscle meat-weight) in 1993 and were valued around AUD$30 million (Kailola et al., 1993). In recent years, fishery productivity and performance has declined. The reported annual scallop harvest of 177 t in the 2016 fishing-year was the lowest in the mandatory logbook database, which commenced in 1988. There has been growing concern among otter-trawl fishers, fishery managers and scientists over the decline.
The fishery concerns resulted in the Queensland Department of Agriculture and Fisheries (DAF) undertaking a stock assessment of saucer scallops in mid-2016 (Yang et al., 2016). Findings showed that standardised catch rates from January 2015 to April 2016 were the lowest on record. These low catch rates indicated that the spawning stock in 2015 was at or less than 20% of early estimates in 1977 (Yang et al., 2016), therefore demonstrating that the stock was overfished.

Publication of the assessment findings in late November 2016 was coordinated with a DAF ministerial announcement on impending changes to fishery management. Important discussions followed between Fisheries Queensland (FQ within DAF), and scallop trawl fishers and processors in Tin Can Bay, Hervey Bay and Bundaberg.

The scallop stock assessment was independently reviewed to confirm conclusions (Rago and Hart, 2017). The independent review said:

'*The stock* is *at best in the "Transitional-depleting" category, and may very well be in the "Overfished" and/or "Environmentally limited" categories. With regards to distinguishing between the latter two categories, it is clear that poor productivity, i.e., "environmental limitation" has contributed to the recent declines. On the other hand, the declines, by their very definition, indicate that the fishery has removed more than the stock could naturally replenish, which implies that the stock is beingoverfished.*'

While fishing contributed to the low abundance of scallops, the influence of environmental conditions was unclear, and no harvest control rules were in place to prevent overfishing. Given these considerations, fishery management introduced a series of closures to prevent further declines, while allowing some harvest to support fishers and processors income.

The new scallop fishing closures were from the 3rd January 2017. All six scallop-replenishment-areas (SRAs) located off Yeppoon, Bustard Head and Hervey Bay remain closed until further notice (Figure 1). In addition, fishers cannot take or be in possession of scallops in the regulated waters between 1st May and 31st October (the extended spawning season) each year.

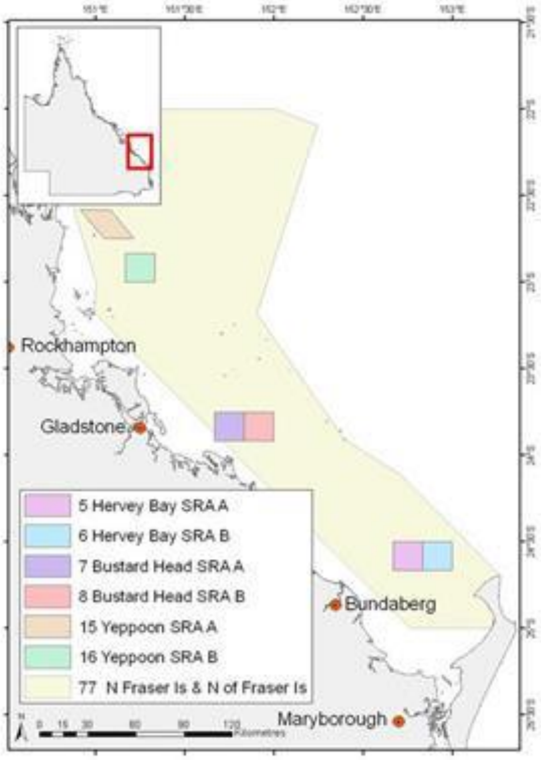

Figure 1. Scallop replenishment areas.

There is now a need to understand the respective roles of fishing effort and environmental drivers on scallop abundance, specifically in relation to the current poor state of the stock. There is also a need to clarify management procedures that are appropriate to the causes of the current poor stock status of scallop.

As most of the scallop fishery is located in waters of the Great Barrier Reef Marine Park (GBRMP), which is a World Heritage Area, there is an obligation to maintain biodiversity and ecosystem services. In addition, there is a need to maintain the Wildlife Trade Operation approval, which is required for processors to export scallops.

Results from this study, and the parallel FRDC project 2017-048, will assist stakeholders and the fishery's managers to rebuild the scallop stock. The outputs will also assist addressing the terms and conditions required by the Australian Government to sustain the stock.

This project undertook analyses of fishing and environmental influences on scallops, to improve predictions for management and stock indicators. The improvements include increasing model efficiency and improving data inputs such as standardised catch rates and environmental influences. For saucer scallops, the project addresses the FRDC National RD&E priorities: 1) well managed sustainable fisheries and 3) maximising benefits from fisheries.

1.2 Scallops and the fishery

1.2.1 Saucer scallops

The Australian east coast 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 (Figure 2). They can potentially grow to about 14 cm in shell height and, in some instances, live for at least 4–5 years (Dredge, 1985; Campbell et al., 2010b). Saucer scallops on the main fishing ground between Yeppoon and Hervey Bay are a single population (stock) (Dredge, 2006), with scallops that spawn east of K'gari likely to be less connected to the main ground.

Figure 2. Saucer scallops.

The scallop adductor meat is a delicacy and sold without roe. Nationally and internationally, they command a premium price, with public Queensland retail prices observed in order of AUD$50 per kilogram of meat. Individual meat weights typically range 7–14 g per scallop. The average meat condition and weight varies seasonally, and is higher between December and March.

The saucer scallop can swim short distances, which suits the otter- trawl fishing method. Scallops tend to sit or partially bury on the bottom, but when the net ground line disturbs the sea floor, they swim upwards and are then efficiently caught in the trawl net.

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 4–5 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.

Scallops feed on minute marine plants and animals, which they catch from seawater by a filtering mechanism involving the gills and cilia. Large fish, turtles, rays, squid, octopus, bugs, crabs and sea stars are natural predators of scallops.

1.2.2 The fishery

Otter trawling for scallops in Queensland is generally by vessels 15–20 m in length. The vessels typically have main engines of 300–400 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.

Trawl efficiencies can range between 20–62%. Joll and Penn (1990) estimated otter-trawl efficiency of about 62% based on Leslie-DeLury depletion experiments. Miller et al. (2019) estimated dredge-trawl efficiencies between 27% and 40% using paired photographic-dredge tows. Herein, the project considered the full published range of trawl efficiencies to catch scallops between 20% and 62%, and the effective width of the trawl path was equal to the distance between the otter boards (Joll and Penn, 1990; Miller et al., 2019).

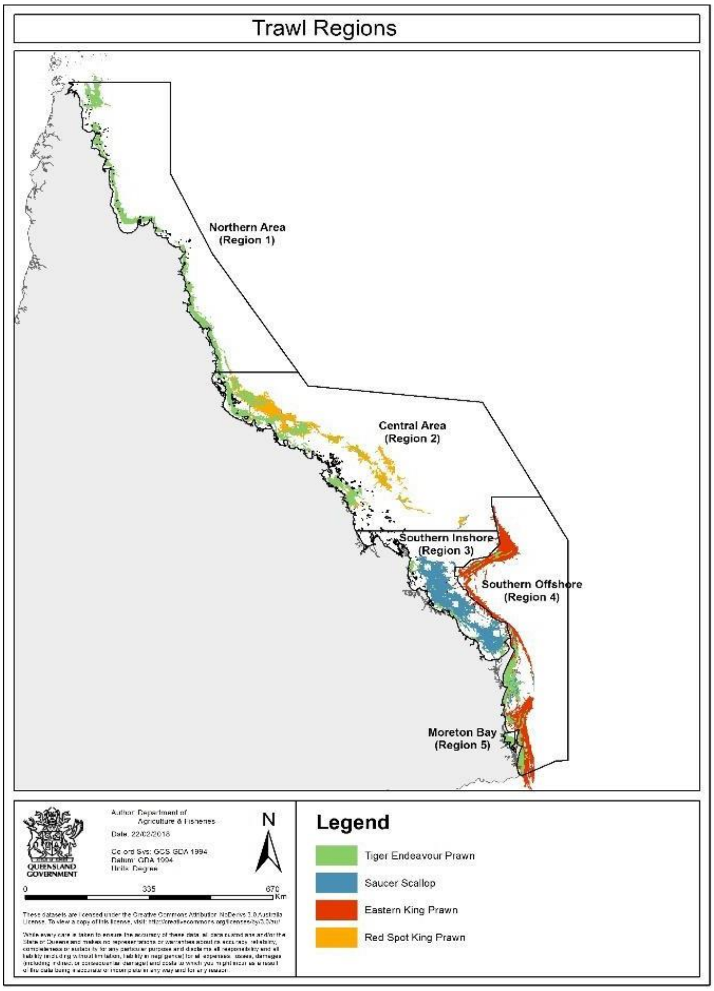

Figure 3. East coast trawl fishery divided into five management units (Department of Agriculture and Fisheries, 2019). The scallop sector is region 3, south of 22° S to Hervey Bay.

Management of scallop fishing has varied over time. Knowing these changes is important for understanding trends in the fishery data (Table 2). Harvests before 1988 had smaller minimum legal size limits (MLS commercial shell height of less than 9 cm). From 1989, 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 (noted above and Table 2), although these were fished rotationally from 2001 to 2016. Some Great Barrier Reef Marine Park green zone closures also fringe the scallop trawl area (shown below in Figure 4).

New management proposals are in discussion to reform the Queensland east coast otter trawl fishery (Department of Agriculture and Fisheries, 2019). The proposals consider the need to better control fishing effort at the species level, and this is desirable for the sustainability of this scallop fishery. Currently in 2019, each trawl vessel owns effort units (eu) defined as allocated fishing days multiplied by standardised hull units (a measure of the vessel's fishing capacity, O'Neill and Leigh, 2006), which can be fished on any permitted trawl species (e.g. prawns, bugs and scallops), and generally at any time and area on the east coast.

The future proposal under consideration is to reallocate effort unit limits into a regional total allowable effort, within an east-coast- wide total allowable commercial effort (TACE) limit. This may involve the following aspects (Department of Agriculture and Fisheries, 2019):

- Divide the east coast into five regions based on the major target species fished (scallop is region 3, Figure 3).
- Set regional effort limits for maximum sustainable yield (MSY) or less, and adjust as needed through fishing-effort control rules.
- Allocate effort units to those regions based on fishing history from vessel tracking data.

Table 2. History of fishery management for saucer scallop.

Description	Date	Management Plan
Shell Height (SH)	1977	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’ (SRA)
	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

1.3 Scallops and their ocean environment

1.3.1 Oceanographic

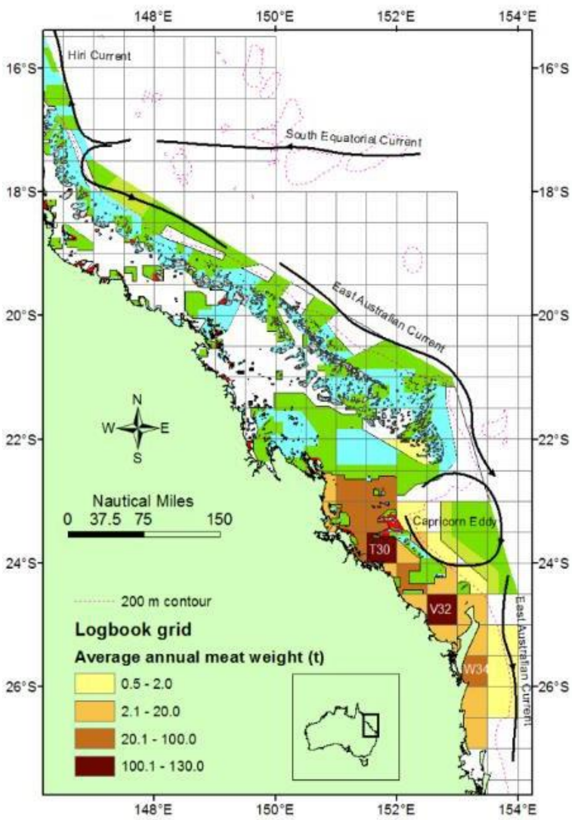

Figure 4. Harvest distribution of the scallop fishery 1988–2013 and the Capricorn Eddy. The blue, green and red are zones in the Great Barrier Reef Marine Park.

Associations of environmental trends on Australian fisheries and marine species has been a focus of research in the last decade. A review of recent Australian literature from 2009 to 2015 stated that over 400 publications have investigated the impact of marine climate change on fisheries (Ling and Hobday, 2019). A number of these studies investigated climate change associations on fish and invertebrates. The studies primarily investigated effects of ocean temperature warming, circulation, sea level, weather and some environmental influences originating from human activity.

For Queensland saucer scallops, recent studies have identified some key oceanographic influences on scallops (Morison and Pears, 2012; Courtney et al., 2015).

A survey by Morison and Pears (2012) concluded that the health and productivity of scallops may be reduced by higher sea surface temperatures, ocean acidification, changed rainfall patterns, increased tropical storm intensity and flooding, and altered ocean circulation.

This reduced health could be related to their sedentary life and reliance on the quality of available habitat. Changed ocean currents, higher sea surface temperature and ocean acidification could disrupt spawning patterns and volume, and recruitment success.

Courtney et al. (2015) investigated some of the above associations quantitatively, analysing associations of scallop abundance with measures of freshwater flow, sea surface temperature, sea level, strength of ocean currents from the Capricorn Eddy, chlorophyll-a and the southern oscillation index. In summary, the research found many associations with November catch rates of legal-sized scallops. Some of the key results of Courtney et al. (2015) were:

- Elevated sea surface temperatures during the winter spawning period were associated with lower catch rates of scallop the following November. The association could signal reduced scallop recruitment or reduced juvenile survival rate.
- Ocean currents and sea levels from the Capricorn Eddy (see Figure 4) correlated with sea surface temperatures. Increased temperatures from the eddy current associated with lower catch rates.
- Chlorophyll-a associations varied spatially, and appeared to have positive short-term effects.
- Positive associations of fresh water flow from adjacent river systems to the fishery; this result may correlate with preliminary chlorophyll-a findings.
- No significant associations for the southern oscillation index.
- Movements of larval scallop were dependent on ocean current strength and direction, and larval swimming behaviour in the water column. Modelling suggested self-seeding (spawning and recruitment) within the key fishing areas of Yeppoon, Bustard Head, Hervey Bay, and east of K'gari. These areas were important for sustaining scallops.

The results of Courtney et al. (2015) reinforced the high complexity and interactive influences on scallop life histories. However, for the purpose of stock assessment and management planning, it is ideal that key processes be clearly identified.

Courtney et al. (2015) tested the use of three environmental variables to determine if they improved a stock assessment. Using the scallop model of Campbell et al. (2012), the environmental information was included to predict annual recruitment of young scallops. Use of chlorophyll-a produced no improvement. Use of whole-fishery or Capricorn Eddy sea surface temperatures from the previous 22–23 months, resulted in improved model fits, and improved prediction of scallop recruitment. The result translated to an annual maximum sustainable yield (MSY) of 468 t for the sea surface temperature data, and 526 t without, covering Queensland waters south of 22° S. A constant natural mortality rate defined the spawner recruitment relationship and MSY.

Further exploratory analyses using the spatial age-structured model of Campbell et al. (2012) found no evidence that environmental drivers could aid prediction of scallop recruitment (Madden, 2016). This may imply that there is insufficient data to detect environmental effects on recruitment, or that if environmental drivers are significant then they may affect a different life-cycle stage (Madden, 2016). The latter comment was relevant to investigate an environmental effect on scallop survival dynamics, rather than recruitment alone. Even though the Madden (2016) conclusion was different, the results of Courtney et al. (2015) did suggest that estimating recruitment anomalies was better than using environmental information to predict past annual recruitments of new scallops.

Improving stock assessment with a key environmental relationship was one objective of this project, in order to inform management procedures. This project further investigated the Courtney et al. (2015) environmental associations for sea surface temperatures and chlorophyll-a. The relative roles played by these environmental and fishing influences on scallops needed to be qualified, and if clear and uncomplicated, accounted for in stock assessment and management procedures.

1.3.2 Seabed habitat

Knowledge of seafloor features such as hardness, sediment composition and structural macrobiota to classify seabed habitat could help improve measures of fishing pressure on scallop and stock assessment advice. Only preliminary habitat information was available to this project, from sister FRDC project 2017-048, and suggested that scallops were generally associated with sediments containing low levels of mud. This habitat information and the concepts of use are below. More research, from the project 2017-048, will better clarify seabed habitats and relationships with scallop aggregations.

Knowledge of spatial patterns of scallop aggregation and their seabed habitat, matched against spatial patterns of fishing, can improve estimates of fishery area, scallop densities and population size. More importantly, this information can improve management results by accounting for spatial variability in fishing through measurement of harvest rate fractions.

Normally, fishing effort applied in a highly preferred scallop habitat results in higher harvests than the same effort applied in a less suitable habitat. If scallop habitat can be categorised and mapped with predictive densities, this information can improve estimates of scallop mortality. This refined habitat and density estimation could likewise refine management planning controls, such as optimal numbers of fishing vessels and effort.

Adjusting measures of fishing mortality for habitat type has received increased attention because more fisheries are monitoring fishing effort with higher spatial resolution tools, such as vessel monitoring systems (VMS) (Smith et al., 2017). To investigate these ideas, FRDC project 2017-048 is collecting data on seabed type within the scallop fishery. Relationships between physical properties of the seabed (e.g. percentage gravel, percentage sand, percentage mud, percentage carbonate and bottom hardness) and scallop abundance will be assessed.

Preliminary analyses of associations between sediments and survey data from the years 1997–2000 showed a positive correlation between scallop density and sediments containing less than 5% mud (Figure 5).

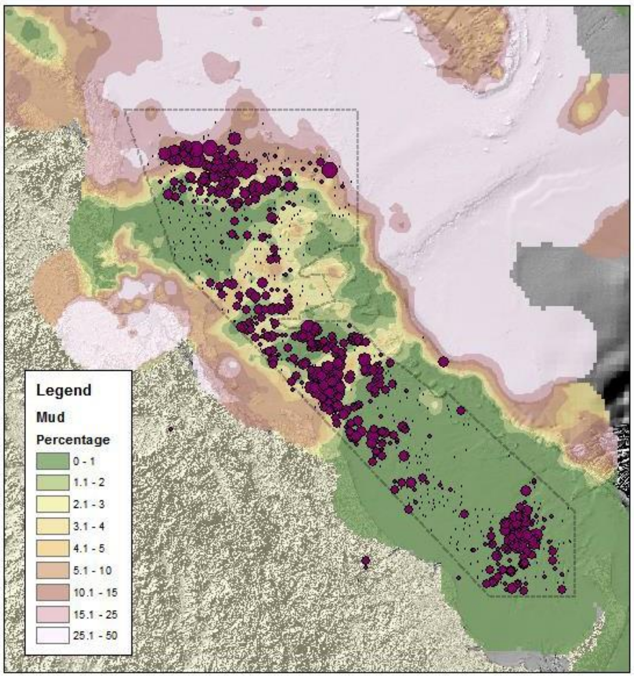

Figure 5. The mud content (%) in sediments from the central Queensland coastal region and the relative abundance of scallops obtained from surveys from 1997–2000.

FRDC project 2017-048 is also using multi-beam echo-soundings (MBES) to derive information on the seabed, to examine seabed profiles affecting the distribution and preferred habitat of saucer scallops. Analysis of existing and new MBES datasets will cover part of the scallop fishing grounds. In addition, seabed sediments, sediment cores, underwater video/photography, oceanographic sensors, satellite imagery and GIS will expand information on the seabed.

Existing MBES data provide high spatial resolution of the underwater depths of the ocean floor for the Hervey Bay zone, which is an important area in the scallop fishery. The left-hand map in Figure 6 illustrates the paleo-channel of the Mary River system, which formed in the previous ice age, as well as dunes in the southern bay. The right-hand side of Figure 6 shows a high spatial resolution TrackMapper image of the intensity of scallop trawl fishing effort (in hours, from VMS data). The intensity of fishing effort in the area is around properties of the paleo-channel, which may relate to seabed hardness of the channel.

When complete and available, the seabed habitat information will be used for refining later stock assessments. Despite that, the population modelling herein has factored for measures of fishery area based on trawl survey, VMS and TrackMapper information.

The above descriptions are examples of how the physical properties of the seabed may help identify the preferred habitat of saucer scallops. Eventually, such combined information will classify the entire sea floor throughout the scallop fishery. This information could improve measures of fishing pressure and hence improve fishery management. FRDC project 2017-048 will inform more on the relationship between seafloor properties and scallop abundance.

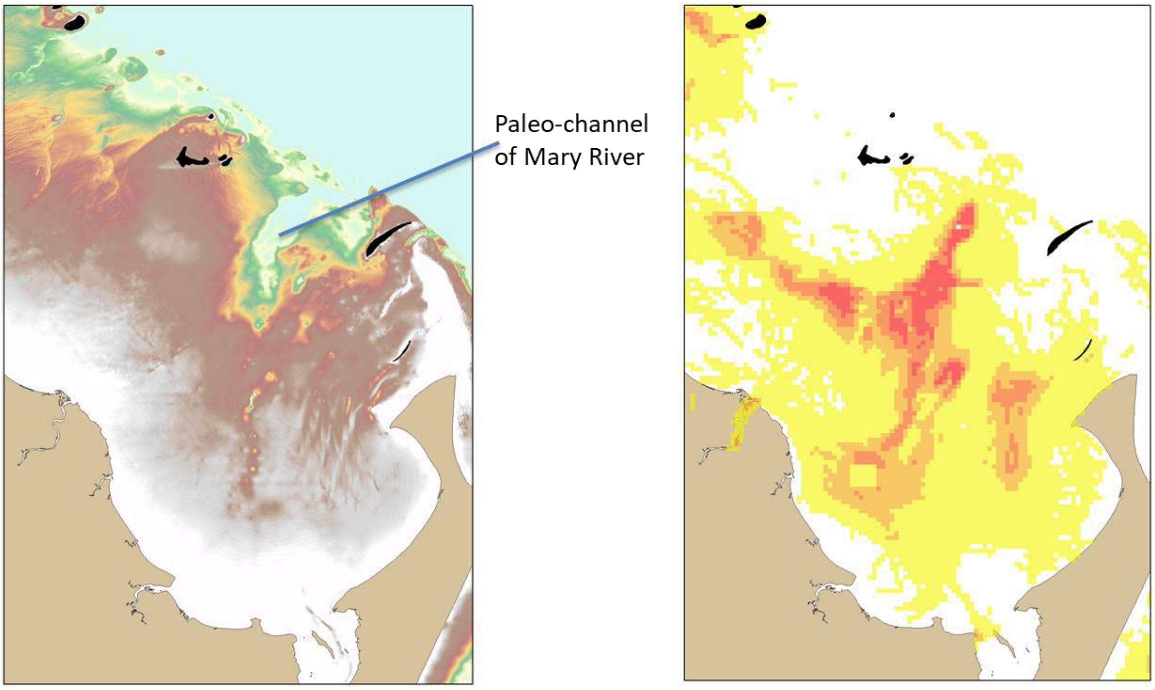

Figure 6. The image on the left shows high spatial resolution bathymetry in the Hervey Bay area, including bottom dunes and the paleo-channel of the Mary River. The image on the right shows high spatial resolution scallop trawl fishing effort (in hours trawled where yellow is few hours and red is high fishing effort). High fishing effort is associated with the paleo-channel.

1.4 Past FRDC research and assessment results

Several research assessments have occurred since scallop abundance declined in 1996 (Yang et al., 2016). The following summary was assembled from the briefing of Yang et al. (2016):

- In 1998, an age-structured population analysis predicted strong recruitment of scallops in 1992, estimates for weak recruitment for 1991, 1993 and 1996 (Dichmont et al., 1999).
- The 2005 age-structured analysis estimated the exploitable biomass in 1997 to be less than the biomass for maximum sustainable yield ($B_{1997} < B_{MSY}$), but higher, close to B_{MSY}, in 1999–2001

(O'Neill et al., 2005). MSY was near 600 t for waters south of 22° S to Hervey Bay.

- In 2010, results suggested the scallop replenishment areas should not be removed and closure times should be increased to 3–4 years to ensure successful spawning and recruitment of scallop (Campbell et al., 2010a). Investigation of vessel monitoring system (VMS, latitude and longitude spatial coordinates) data revealed high trawl intensities for the opening of scallop replenishment areas.
- In 2012, the age-structured analysis was expanded to better model scallop aggregations and long-term 1977–2009 standardised catch rates (Campbell et al., 2012). The results varied depending on the parameters and data used. Modelling of the long-term data suggested the spawning population (stock) ratio S_{2009}/S_{1977} was low at 27% and the stock was near the overfished level of 20% (Fisheries Queensland, 2017). Estimates increased to B_{MSY} or above when down weighting or removing early 1977–1987 data. MSY was near 550 t, for waters south of 22° S including K'gari.
- Also in 2012, a risk evaluation was published on the chance of overfishing scallops (Pears et al., 2012). The evaluation of literature and expert/stakeholder opinions suggested low risk based on assumed species resilience and impact profiles.
- In 2015, as described on page 4, research identified associations between scallop catch rates and environmental variables, particularly chlorophyll-a, sea surface temperature anomalies and physical features of the Capricorn Eddy (Courtney et al., 2015). A stock assessment with the environmental data estimated MSY near 468 t when the sea surface temperature data were included, and 526 t when they were not. This was for waters south of 22° S including K'gari.
- The 2016 stock assessment, using the model of Campbell et al. (2012) with long-term data, estimated low spawning ratios of 5–10% of 1977 levels. Estimates were higher at 20–50%, when 1977–1987 catch rate data were excluded. No MSY or reference points were calculated.

The work herein focused on using all long-term data, which better reflects the recent status of the scallop fishery. Down weighting or removing early data tended to confuse past results and messages, and estimates varied with larger confidence intervals.

2 Objectives

The objectives as stated in the proposal were:

1. Design stock model structures and estimate parameter values for the associations between saucer scallop abundance and environmental variables, including scenarios of scallop recruitment changing in parallel with changes in areas of the different habitat types.
2. Improve spatial indicators and stock model predictions to estimate the current population size of saucer scallops and develop management procedures.

For clarification, the first objective only considered the measure of the overall fishery area relative to the inclusion of survey scallop densities from the project FRDC 2017-048.

Data on sea-bottom hardness, derived from multi-beam echo soundings, sediment type and grain size are being collected under the FRDC 2017-048 project, at the time of writing this report. In addition to the habitat data and mapping, FRDC 2017-048 is also deriving new estimates of the saucer scallop's natural mortality rate (*M*), which will also be incorporated in future assessments of stock. This new information on habitat and *M* is not yet available because FRDC 2017-048 has a longer project duration and later completion date than the present FRDC 2017-057 project. Subsequently, this information will be for refining future stock assessments.

Study design and analytical selections for this study were made using the most up to date data and information available.

A proposed management procedure (harvest strategy) framework is under design by Fisheries Queensland. The framework will consider a selection of status indicators and reference points for the region 3 fishery (shown in Figure 3).

3 Methods

3.1 Harvests and catch rates

The scallop harvest and catch rate information were obtained from four data sources (Table 4). Each data set played an essential part in building the data inputs to the stock assessment model and overall description of the scallop fishery. Protocols for processing the data were previously published (O'Neill et al., 2005; O'Neill and Leigh, 2006; Campbell et al., 2010a; Campbell et al., 2012; Yang et al., 2016). This is summarised below and in the Appendix 12.1 (Table 14, Table 15, Table 16 and Table 17, page 71).

The scallop fishery spatial domain was between 22° S and 27° S latitudes, along the east coast of Queensland, Australia. Logbook species codes included 'scallop – unspecified' (23270000), 'scallop – saucer' (23270001), 'scallop – mud' (23270003) and 'scallop – queen' (23270005). Only minor reports of harvests were against the non-saucer scallop codes, more so in early logbook years than later years.

The time series structure of data was by fishing years and calendar months, from November to October. For example, fishing year label 2018 was from November 2017 to October 2018 where November was fishing month 1 and October was fishing month 12.

Spatial structure of the data was by ten spatial areas (six of which were scallop replenishment areas), covering four large zones, as summarised in Table 3 (also displayed graphically in Figure 42, page 70, Appendix 12.1).

Table 3: A summary of the spatial structure of the fishery, separated into zones and areas.

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)
K'gari area	K'gari area

Scallop catch rate analyses used daily information by the four large zones (Figure 43, page 70, Appendix 12.1), using key fishing grids and species criteria (Appendix 12.1, Table 14, Table 15, Table 16 and Table 17, page 71). The catch rate data included approximately 95% of all catch and effort data. Tallies of scallop harvest, however, used all daily and bulk (> daily) catch information by ten areas and all waters within the fishery domain.

All harvest data (logbook-reports) were recorded as number of scallop baskets, and converted to kg meat weight where required. Harvest statistics were in terms of fishing years and months from November to October. In general, a basket of whole scallops weighed about 28–43 kg (pers. comm. Zeller and Courtney, 2019). For meat weight, a basket of scallop weighed 5.0–7.5 kg (O'Neill et al., 2005). Basket capacities vary with the size of scallops, and meats weigh less during winter spawning (Table 29, page 80, Appendix 12.4). For a 9 cm sized scallop, an approximate ratio of whole-shell to meat weight was 5.7 (Williams and Dredge, 1981).

Table 4. List of harvest and catch rate data

Time series	Data	Description
Jan 1956–Dec 1987	Historical data	Total annual meat weight harvest in tonnes by calendar year (Dredge, 2006).
Jan 1977–Dec 1987	HTrawl	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 (O'Neill et al., 2005; O'Neill and Leigh, 2006; Yang et al., 2016). Records in baskets. This dataset was based on 5–30% per year of fishers voluntary participation in the logbook program (O'Neill and Leigh, 2006).

Jan 1988–Oct 2018	Commercial Logbook or CFISH	Daily basket and effort data from compulsory commercial logbook data in 30×30 minute grids.
Nov 2000–Oct 2018	Vessel Monitoring System (VMS) and TrackMapper	Effort data from VMS tracking data. The spatial scale of these data were finer than the logbook data.

Harvest levels from the historical data (Table 4) suggested that the fishery was built from around 1956. 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. The research presented in this study differed from previous assessment reports of Campbell et al. (2012) and Yang et al. (2016), in that the assumed first year of the scallop fishery was changed from 1977 to 1956. By starting in 1956, analyses utilised more data and enabled a better account of the history of fishing.

The historical harvest data (Dredge, 2006) were total annual tonnages of scallops by calendar year 1956–1987. The steps to convert tonnages into number of baskets, for ten areas and each fishing year and month are in Table 5. The steps listed in Table 5 used a generalised linear model (GLM) for scallop catches (baskets), setup with an over-dispersed Poisson distribution and logarithm link function. The GLM terms considered different fishing years, and months by areas, to define seasonal patterns for the annual data.

Table 5. Conversion of historical harvest data by annual weight and calendar year to number of scallop baskets by fishing year, month and ten areas.

Step	Description	Method
1	*Fishing month and logbook grid conversion*: Converted the annual data to fishing month and seven logbook grids.	A Poisson GLM analysed the HTrawl data for 1977-1988 to give the proportion of baskets harvested by fishing month and seven logbook grids (Yeppoon, grid S28, Bustard Head, grid T30, Hervey Bay, grid V32 and K'gari). This was: MODEL [DISTRIBUTION=Poisson; LINK=logarithm; DISPERSION=*] baskets FITINDIVIDUALLY fishyear+fishingmonth*sevengrids The proportional distribution by fishing month and seven logbook grids split annual data to give harvest (in tonnes) by fishing year, fishing month and seven logbook grids (Table 18, Appendix 12.1, on page 72).
2	*Ten-area conversion*: Converted the data from step 1 to ten areas.	Trackmapper (using VMS data November 2001–October 2018) calculated the average monthly proportion of harvest for splitting: grid S28 into Yeppoon, YA and YB; grid T30 into Bustard Head, BHA and BHB, and grid V32 into Hervey Bay, HBA and HBB. The calculations gave harvest in tonnes by fishing year, fishing months and ten areas. See Table 19, Appendix 12.1, page 73.
3	*Baskets conversion:* Converted tonnes in step 2 to baskets.	The conversion of meat weights to baskets used Table 29, Appendix 12.4, on page 80.

The collations and processing of the HTrawl catch-rate data were in previous projects (O'Neill et al., 2005; O'Neill and Leigh, 2006; Yang et al., 2016). The data represented voluntary-logbook-reported daily scallop harvests (in baskets, per vessel day and grid) between 1977 and 1987, prior to the implementation of the compulsory CFISH logbook system in 1988. Table 8.3.7.1 in Project No 1999/120 (O'Neill et al., 2005) describes the historical trawl data.

Yang et al. (2016) made minor changes to the HTrawl data in 'revisedglmdata.gsh', and examined catch rates from 11 vessels common in the pre- and post-1988 logbook data sets. The catch history of the 11 boats indicated that all but one vessel showed a long-term decline in their catch of scallops, both in daily catch of baskets, as well as daily catch of baskets per hours fished. The single vessel without a sharp decline in catch rates did not have high catch rates in 1980 and 1981. The reasons for this were not known (Yang et al., 2016). The investigations of the HTrawl data by Yang et al. (2016) provided no evidence to contradict a decline in scallop catch rates to 1987.

Despite the 1977–1987 decline in catch rate (shown in Figure 20, on page 33), results depend on the assumption of proportionality of catch rates to scallop abundance. The amount of HTrawl spatial and temporal data from 1977–1987 was less than that of the compulsory harvest reports after 1987. Further, there is a need to investigate the decline in catch rates to exclude questions on the amount of bias by time and space in the data, and influence of spatially aggregated fishing to cause depletion in catch rates during 1977–1987. These questions and caveats are pivotal, and the methods for catch rate standardisation aimed to address some of the uncertainty and mitigate possible bias. Yang et al. (2016) discussed the data in more detail.

VMS and logbook data, in TrackMapper, provided commercial harvest data from November 2000 to October 2018. All boats had VMS tracking with latitude and longitude coordinates (Good et al., 2007; Courtney et al., 2016). TrackMapper grouped the harvest per vessel from the logbook sources into ten areas. With finer spatial resolution, TrackMapper data calculated average monthly proportions of scallop baskets in the ten areas, to split the historical Dredge (2006) annual harvest summary. Generally, vessels only fished one area per night, even for the SRAs (Figure 44, page 73 in Appendix 12.1).

For the logbook spatial grid data 1988–2018, it was possible to divide the number of scallop baskets harvested by fishing year, month, day, vessel and four zones, namely Yeppoon (logbook grid S28), Bustard Head (logbook grid T30), Hervey Bay (logbook grid V32) and K'gari. Rules from step 3 in Table 5 and VMS data further divide harvests into areas: logbook grid S28 into harvest from Yeppoon, YA and YB; logbook grid T30 into Bustard Head, BHA and BHB; and logbook grid V32 into Hervey Bay, HBA and HBB. This produced the harvest data in the required format for stock model input.

Catch rate analyses were limited to a four-zone spatial stratification. The ten-area approach above for total harvest was less reliable for catch rates 1977–2018, due to overly reducing the number of data per strata compared to the number of REML parameters for different fishing years, months, areas and vessels.

The time series of standardised catch rates of log-transformed baskets of scallops per boat-day were analysed through linear mixed models. Four catch rate standardisations investigated temporal and spatial patterns of legal sized scallop abundance. The analyses were for:

1. Fishing **year by month by zone** trends, using only data from **January 1988 – October 2018**. This analysis investigated **four zones**, and only used the mandatory CFISH logbook data (not the HTrawl data from 1977–1987). Logbook grids, nested within the variable "zone", were a random effect.

```
VCOMPONENTS [FIXED= zone*fishyear*fishingmonth+loghours+loghp+logspeed+sonar+gps2+nettype+ggear4+boards;
FACTORIAL=2] RANDOM=boat_mark+grid; REML logn
```

2. Fishing **year by month by zone**, using data from the longer period **January 1977 – October 2018**. This analysis investigated **four zones** and included both the voluntary HTrawl data (1977–1987), and the mandatory CFISH logbook data (1988–2018). Boat marks identified all fishing vessels across the data. This analysis factorised the four large zones, and offset vessel gear information from analysis 1. The vessel gears for HTrawl data 1977–1987 were as in past data and reports (Table 24, page 76) (O'Neill et al., 2005; O'Neill and Leigh, 2006; Yang et al., 2016). The gear data were also relevant for the fourth standardisation summarised just below.

```
VCOMPONENTS [FIXED= zone*fishyear*fishingmonth+loghours; FACTORIAL=2] RANDOM=boat_mark;
REML lognoffset
```

3. Fishing **year by month** trend. This was similar to analysis 1, for **January 1988 – October 2018**, but removed the K'gari data. The result focused on a single fishing year × month catch rate index for the combined fishing ground (for the proposed **management region 3**, Figure 3), rather than zone

interactions. The K'gari data were removed for this analysis because this zone is located outside of the main fishing grounds. K'gari is associated with irregular and infrequent scallop catches, and because of the relatively high catch rates associated with the area in 2017, it may mask the overall trend in catch rates in recent years, if included.

```
VCOMPONENTS [FIXED= fishyear*fishingmonth+loghours+loghp+sonar+gps2+nettype+ggear4; FACTORIAL=2]
RANDOM=boat_mark+grid; REML logn
```

4. Fishing **year by month** for **January 1977 – October 2018** (similar to analysis 2), but removed the K'gari data. The result focused on a single fishing year × month catch rate index for the combined fishing ground for the proposed **management region 3** (Figure 3).

```
VCOMPONENTS [FIXED= fishyear*fishingmonth+loghours; FACTORIAL=2] RANDOM=boat_mark+grid;
REML lognoffset
```

Catch rates were standardised to a typical modern vessel, namely a vessel with about 337 HP, fishing for 12 hours (full nights fishing), with sonar, GPS mapping, quad gear and drop chain.

The datasets and methods herein for the catch rate standardisations were collated and built from the projects O'Neill et al. (2005), O'Neill and Leigh (2006), Campbell et al. (2010a), Campbell et al. (2012) and Yang et al. (2016). The catch rate standardisations used the statistical application of linear mixed models (LMM) using restricted maximum likelihood (REML). The analyses used daily logbook information.

As in previous projects, catch rates were standardised for changes in fishing power through time due to 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 12.7 for trends in vessel gears, on page 98.

The standardisation models 1–2 included a fixed zone term that had not been included in previous standardisations. Thus, models 1–2 produced a series of monthly average catch rates for 1988–2018 or 1977–2018, by four zones.

The LMM (REML) theory correlated the logarithm of catch $\boldsymbol{C}$ in baskets to covariates: 1) $\boldsymbol{X}_1$ which included zone, fishing year and fishing month as factors and the associated interactions; 2) $\boldsymbol{X}_2$which included the logarithm of hours (fished) and engine horse power (HP), trawl speed, the use of sonar and GPS, net type ground gear type and boards; 3) $\boldsymbol{\gamma}$ included vessels. The structure of the LMM was as follows:

$$\log(\boldsymbol{C}) = \beta_0 + \boldsymbol{X}_1\boldsymbol{\beta}_1 + \boldsymbol{X}_2\boldsymbol{\beta}_2 + \boldsymbol{Z}\boldsymbol{\gamma} + \boldsymbol{\epsilon},$$

where β_0 was the intercept, $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_2$ were vectors of coefficients associated with the data $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$, respectively, $\boldsymbol{\gamma}$ were vectors of random effects for vessels, and fishing grids where used, following a Gaussian distribution with mean zero and constant variance σ_{γ}^2, and $\boldsymbol{\epsilon}$ was a vector of errors following a Gaussian distribution with mean zero and constant variance σ^2. Specifically, $\boldsymbol{\beta}_1$ represented scallop abundance and $\boldsymbol{\beta}_2$ the fishing efforts and powers. Coefficients and variances were estimated using REML via the statistical package GENSTAT 19 (VSN International, 2018).

For prediction of standardised catch rates, the fixed term variables were set as outlined in Appendix 12.3 on page 75. The settings were important to ensure the catchability scale for catch rates was appropriate, for later calculating effort based reference points from the population model predicted harvest and catch rates. Therefore, catch rates were for a potential modern fleet. Boat settings were for the maximum annual-average fleet-vessel effect in 2007. Thus, the vessel with a log parameter value closest to the 2007 fleet average set the vessel term for prediction. These settings defined predictions according to a modern vessel-fleet profile, using the 2018 trend for drop chain ground gear, quad net gear, GPS, sonar, about 12 hours fishing per night/day, and 337 engine-horse-power. Mean predictions, from the log scale, were exponentially back transformed and bias corrected by adding half of the model residual variance (McCullagh and Nelder, 1989; O'Neill et al., 2010). Additions or subtractions were also included for calculating confidence intervals, and adjusting for any offsets.

3.2 Environmental variables

This study used statistical analyses to investigate associations between environmental data and scallop catch rates, both temporally and spatially. From this, the identified environmental variables, significantly correlating to the scallop catch rates, helped tune the population model for stock assessment to examine possible environmental impact on scallops. This method section describes the statistical analyses to identify the relevant variables.

Standardised catch rates were employed to represent scallop abundance, as used by Courtney et al. (2015). Analyses used catch rates of November, December and January. Sea surface temperature (SST) and chlorophyll-a (Chl-a) concentration were the considered environmental drivers on scallop abundance. This was based on findings from Courtney et al. (2015). The analyses presented in this study extended the work and findings of Courtney et al. (2015) to include spatial associations patterns using updated SST and Chl-a data, and the November catch rates to fishing year 2018.

The two selected variables, SST and Chl-a, were analysed in two different analyses. One investigated the temporal-spatial correlation patterns between the November catch rates, and SST and Chl-a in preceding months. The other examined the temporal correlation between SST in preceding months and catch rates of November, December and January.

3.2.1 November catch rates (eReefs data source, 2002–2016)

A series of linear regressions correlated November standardised catch rates with environmental influences, both spatially and temporally. November catch rates were selected for use in analyses because:

- There is little fishing effort in the preceding months from May to October, when meat weight is poor due to gonad development and reproductive output (i.e. spawning).
- Scallop abundance is generally at its peak at this time from new recruitment.
- November generally produces the highest catch, accounting for about one quarter of annual harvest.
- There has been a constant minimum legal size (MLS commercial shell height) of 9 cm in November, even though the MLS had varied during other months. Past management had imposed an elevated MLS of 9.5 cm from 1 May to 31 October. This aimed to discourage harvesting of small scallop during these months.

The Chl-a, and SST data were obtained from eReefs (https://ereefs.org.au/ereefs), which provided their spatial information in high resolution. The Chl-a data were monthly data from 7/2002 to 11/2016 with spatial resolution 0.6 x 0.6 minutes. The SST data were also monthly from 4/2002 to 11/2016 with spatial resolution 1.2 x 1.2 minutes. Note that eReefs only provided Chl-a, and SST data north of latitude 25.5° S degrees. The Chl-a, and SST data were used to correlate with November standardised catch rates which were derived for the whole scallop fishery.

Normal linear regression was applied to reveal the spatial associations between the November standardised catch rates and the environmental variables Chl-a, and SST. Let c_y denote November standardised catch rate of year y, and $x_{s,t,y}$ a value of Chl-a or SST at location s at time-lag t in year y. Time-lag t was expressed months before November, where $t = 0, \dots, 18$. The linear regression model correlated the logarithm of November c_y to the environmental variable at locations s at time-lag t as follows:

$$\log(c_y) = \alpha_{s,t} + \beta_{s,t} x_{s,t,y} + \epsilon_{s,t,y},$$

where $\alpha_{s,t}$ and $\beta_{s,t}$ were the intercept and slope and $\epsilon_{s,t,y}$ was an error term following the Gaussian distribution with mean zero and variance $\sigma^2_{s,t}$ Specifically, the slope $\beta_{s,}$ measured the relationship between the logarithm of November c_y and the environmental variable. Its interpretation was that one unit change of $x_{s,}$ changed the November standardised catch rate by $\exp(\beta_{s,t})$.

Parameter estimation and inference was in the framework of Bayesian statistics and completed using MCMCpack (Martin et al., 2011) in the statistical package R (R Development Core Team, 2018). No priors were given to parameters to have less subjective impacts on inferences. Each model analysis conducted 10 000 iterations of Markov chain Monte Carlo (MCMC) sampling, with the first one thousand iterations as burn-in.

3.2.2 November to January catch rates (NOAA data source, longer time series)

Two additional analyses (linear regressions as above) extended information on associations of catch rates with sea surface temperature (SST) data. These analyses included data from two additional key fishing months (December and January).

Analysis 1 used daily Optimum Interpolation Sea Surface Temperature data (OISST) from NOAA (Banzon et al., 2016). The daily OISST data were from September 1981 to October 2018, with a spatial grid resolution of 0.25 degrees. Calculation of monthly OISST was from the mean of daily temperatures.

The linear regressions used c_y denote the standardised catch rate of the selected month of year y, and $x_{t,}$ the SST value at time-lag t in year y. Time-lag t expressed t months before the selected month, where $t = 0, \ldots, 18$. The simple linear regression model regressed the logarithm of c_y on $x_{t,}$ at time-lag t as follows:

$$\log(c_y) = \alpha_t + \beta_t x_{t,y} + \epsilon_{t,y},$$

where α_t and β_t were the intercept and slope, and $\epsilon_{t,y}$ was the error term following the Gaussian distribution with mean zero and variance σ_t^2. Slope β_t measured the relationship between the catch rate of the selected month and SST.

The second analysis extended the SST time series data (“ERSSTv5”) from NOAA (Huang et al., 2017). The data were monthly from January 1900 to October 2018, with a spatial grid resolution of two degrees. The ERRSTv5 data were a time series of mean SST around the scallop fishery.

To predict the SST for the scallop fishery from 1900 to 1981, the OISST monthly SST data were linearly regressed on the ERSSTv5 SST data (R^2=0.6043). The model fitted the data from 9/1981 to 10/2018. Then, the fitted model predicted the SST for 1900–1981, given the ERSSTv5 SST data for those years.

Figure 7 illustrates that ERSSTv5 covered the scallop fishery less than OISST. The OISST data provided a more suitable spatial correlation with scallop catch rates. ERSSTv5 was used to hindcast OISST to 1900.

Hind casting was to enable annual winter SST data for the population model analysis, where the scallop fishery and data were from 1956.

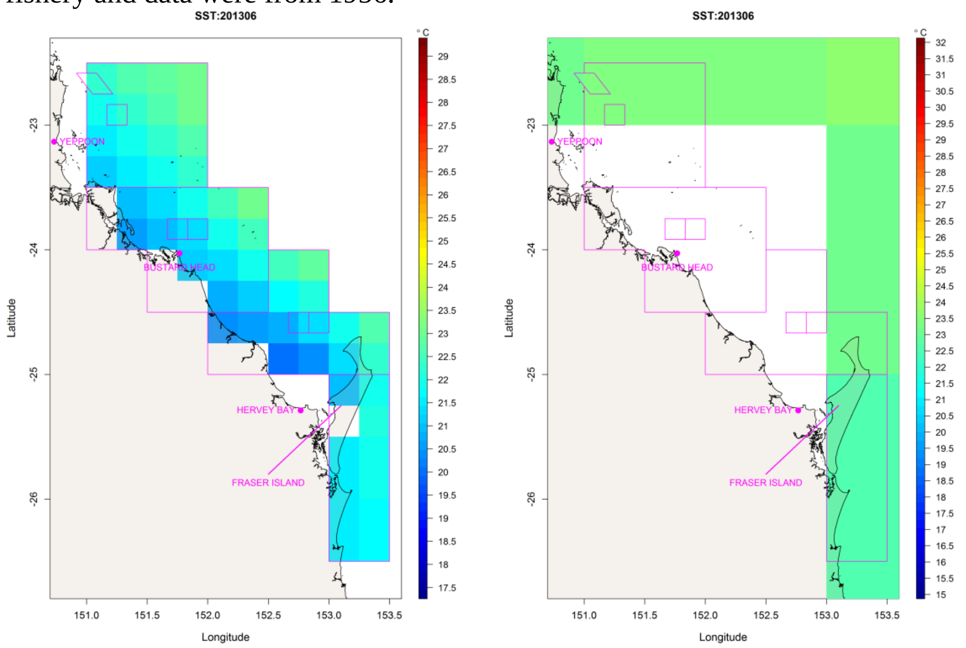

Figure 7. The spatial distribution of OISST (left panel) and ERSSTv5 (right panel) in June of 2013.

3.3 Mapping and surveys

3.3.1 Surveys

A fishery independent trawl survey provided the scallop density data (number of scallops per hectare). The survey focused on scallops grouped by age (0+ or ≥1+, depending on their size) in October of years 1997–2006 and 2017–2018. In addition, for 2018, density estimates of commercial sized scallops informed on potential fishery yields. This was for an assumed precautionary catchability value of 0.6205 (Joll and Penn, 1990). The methods outline the density data appropriate for the stock modelling.

The model presented herein was adapted to use the most recent survey data (as per FRDC project 2017-048), conducted under a random, stratified design. The survey area covered the fishery domain in 1997– 2000 and 2017–2018, but was largely restricted to the SRAs in 2001–2006 due to funding constraints.
Sampling east of K’gari (Fraser Island) commenced in 2017 because logbook data over the last two decades indicate increasing catches of scallops in this southern part of the fishery.

Other changes to survey design included the use and analysis of impacts of turtle exclusion devices (TED) and bycatch reduction devices (BRD) in the survey nets, and relatively small changes to the fishery spatial-domain after the expansion of protected green zones. TEDs and BRDs became mandatory after 2000. Since 2004, trawl sampling excluded green zones, as part of the Great Barrier Reef Marine Park (GBRMP) boundaries and Representative Areas Program (RAP).

Normally around 200–400 sites, including calibration sites where all trawlers sampled together, were surveyed each year by two or three chartered otter trawlers. Each site was one nautical-mile long in distance trawled.

Unfortunately, for various reasons, there were some differences in the survey sampling strata between years, and due to the need to use a tender process to charter vessels, there was little control over which vessels participated each year. Calibration analyses, by FRDC 2017-048, aimed to standardise vessel differences. Sampling was largely restricted to SRAs in 2001–2006, and the K’gari sampling was in 2017–2018.

The 0+ age group included scallops < 7.8 cm shell height, and the 1+ age group included scallops ≥ 7.8 cm. The spatial abundance of the two age groups provided insight on scallop recruitment of small shell, and on mortality rates of large scallop. These data were incorporated into the age-based stock model.

Scallop densities for each of the ten areas were estimated using local kriging (geo-statistical interpolation) models on the survey data. Predictions were derived for three groups: 1) 0+ age group for scallop sizes less than 7.8 cm shell height; 2) 1+ age group for scallop sizes larger than or equal to 7.8 cm shell height; and 3) commercial legal sized scallops greater than or equal to 8.8 cm shell height. The 8.8 cm shell height (vertical scientific measure) was equivalent to 9 cm in commercial measurement (maximum shell diameter, from any angle). The predictions were for the commercial fishing grounds.

The kriging model constructed spatial survey densities (number of scallops per hectare) for the survey years. The kriging model assumed scallops were spatially distributed as a Gaussian spatial random field: $(\boldsymbol{s})$: $\boldsymbol{s} \in D$, where D represented the fishery domain. The scallop density data $(\boldsymbol{s}) = [Z(\boldsymbol{s}_1), \dots, Z(\boldsymbol{s}_n)]'$ were the survey estimates at sites: $\boldsymbol{s}_1, \dots, \boldsymbol{s}_n$. With these data, the kriging interpolated the surface of the random field $(\boldsymbol{s})$, and then predicted the scallop densities for the ten areas of the fishery domain.

Local kriging methods suited the spatial aggregating patterns of the scallop population. The reason was that the local kriging conducted a prediction for a site using all neighbouring data around the site (Schabenberger and Gotway, 2005; Bivand et al., 2013). The local kriging method addressed the spatial correlation via the spherical variogram function (d) at distance d as follows (Cressie, 1993):

$$\gamma(d) = \begin{cases} 0 & d = 0 \\ \theta_0 + \theta_s \left(\dfrac{3d}{2\alpha} - \dfrac{1}{2} \left(\dfrac{d}{\alpha} \right)^3 \right) & 0 < d \leq \alpha, \\ \theta_0 + \theta_s & \alpha < d \end{cases}$$

where θ_0 was the nugget effect, θ_s the sill parameter and α the range. The three parameters should each be positive. Spherical variograms are widely used in applied geostatistics (Rivoirard et al., 2000). The Cressie-Hawkins estimator produced the variogram (see Section 2.4.3 of Cressie (1993); Section 4.4.2 of Schabenberger and Gotway (2005)). The selected neighbourhood size and distance determine the local kriging model.

The prediction of scallop density for each area was formed on small blocks (i.e. $\boldsymbol{B}$ with area $|\boldsymbol{B}| = \int_{\boldsymbol{B}} d\boldsymbol{s}$), instead of at a point $\boldsymbol{s}$. Hence, predictions utilised the change-of-support equation (Cressie, 1993; Schabenberger and Gotway, 2005):

$$Z(\boldsymbol{B}) = \frac{1}{|\boldsymbol{B}|} \int_{\boldsymbol{B}} Z(\boldsymbol{s}) d\boldsymbol{s}.$$

The performance of the local kriging relied on the choice of appropriate neighbourhood size, and on fitting spherical variogram. Obtaining an empirical (observed) variogram for fitting required grouping data into distance intervals. The interval widths were from cross-validation of the mean squared prediction error (MSPE).

The cross-validation procedure used a set of values of neighbour hood size and distance. The range of values considered neighbourhood sizes between 10–40 km and distances 3–60 km. MSPE was as follows:

$$\text{MSPE} = \frac{\sum_{k=1}^{n} \left(Z(\boldsymbol{s}_k) - \widehat{Z(\boldsymbol{s}_{-k})} \right)^2}{n},$$

where $\widehat{Z(\boldsymbol{s}_{-k})}$ was the kriging prediction of $Z(\boldsymbol{s}_k)$ when the local kriging was fitted to the whole data points without $Z(\boldsymbol{s}_k)$. The smallest value of MSPE set the neighbourhood size and distance.

For predicting the density of ten areas, the kriging involved dividing each area into 100 thousand square cells. R package "gstat" of version 1.1-6 completed the analyses (Pebesma, 2004; Bivand et al., 2013; R Development Core Team, 2018).

Assumed survey catch efficiencies (catchability) scaled the density estimates up, dividing by the experimental estimates of 0.20, 0.30, 0.40 and 0.6205 (Joll and Penn, 1990; Miller et al., 2019).

3.3.2 Mapping commercial scallop fishing

The commercial scallop harvest and modelling information are essential statistics to manage the fishery. For consistency, it was important that the corresponding survey density estimates of scallops also represented the commercial fishery area.

TrackMapper analysed raw scallop VMS and harvest data, to provide monthly catch and effort data from January 2000 to October 2018 at 0.01 degrees spatial resolution (for information on TrackMapper, see Courtney et al., 2016). Figure 8 illustrates an example of these data, showing the changed spatial distribution of fishing between January of 2012 and January of 2013. The differences and change in spatial distribution of fishing revealed the scallop grounds that vessels had fished over time.

To reveal the broader area of commercial scallop fishing, TrackMapper outlined the areas fished for the VMS data 2000–2018, including all six SRAs. TrackMapper defined the commercial fishing grounds (Yeppoon, Bustard Head, Hervey Bay, and K'gari outside of the SRAs) where monthly fishing effort had been at least one hour between January 2000 and October 2018. For the six SRAs, all fishing effort could describe the fishing area. Figure 9 shows the resulting measure of the commercial fishing area. The areas (in hectares) of the ten areas for the stock model were Yeppoon: 429752.899, YA: 27710.891, YB: 31679.795, Bustard Head: 378212.953, BHA: 31500.696, BHB: 31515.614, Hervey Bay: 264299.154, HBA: 31401.342, HBB: 30400.289 and K'gari (Fraser Island): 231445.439.

The R software environment was used to calculate the area estimates with a set of GIS related R packages: "maptools" version 0.9-4 (Bivand and Lewin-koh, 2018), "rgdal" version 1.3-7 (Bivand et al., 2018), "rgeos" version 0.4-2 (Bivand and Rundel, 2018), and "sp" version 1.3-1 (Pebesma and Bivand, 2005).

Combining the regional area estimates with the predicted scallop densities from kriging, and assumed survey catch efficiencies, provided an estimate of scallop abundance for the stock model.

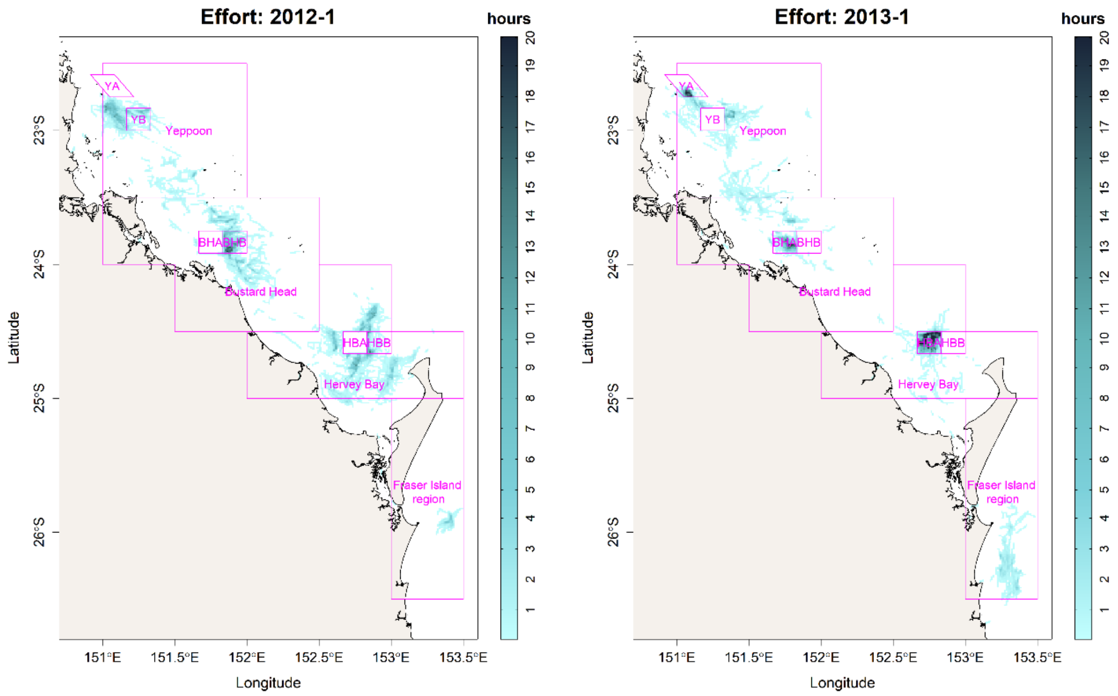

Figure 8. The spatial distribution of TrackMapper analysed scallop-fishing effort (in hours) in January of 2012 (left map) and in January of 2013 (right map).

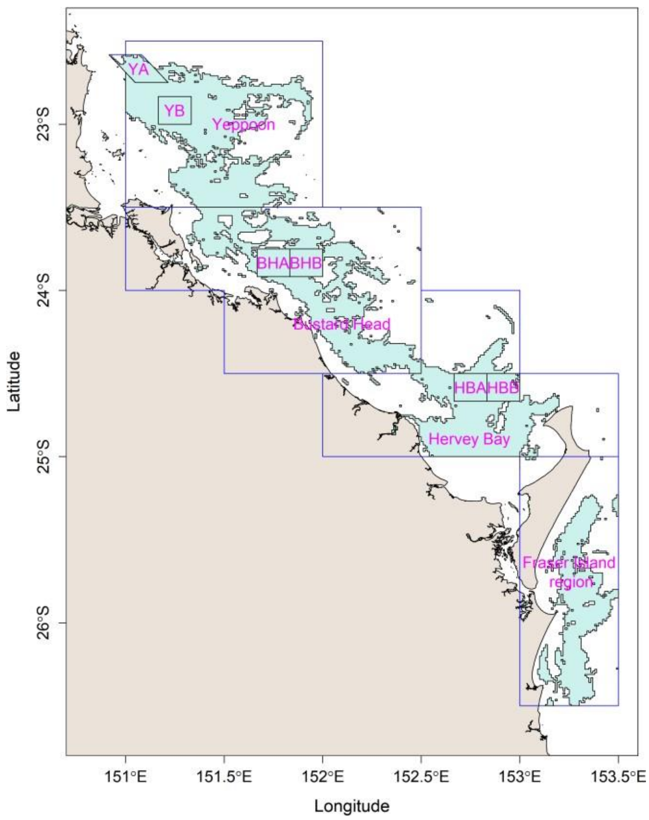

Figure 9. The outline of commercial scallop fishing based on overlapping TrackMapper spatial information from January 2000 to October 2018.

3.4 Population models

3.4.1 Population model with SST mortality integration

The scallop stock model is an age-based population dynamic model, and is catch-driven to estimate fishing mortality. The model is an adaptation of those used by Campbell et al. (2012) and O'Neill et al. (2014), which predicts indicators of scallop abundance for the whole fishery and regionally. It also provides reference points and projections for management procedures to support the Queensland Sustainable Fisheries Strategy.

The model assessed scallops monthly from the fishing years 1956 to 2018, 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 model operated in two phases: (i) historical estimation of the scallop population (stock) from the fishing years 1956–2018 and (ii) simulations of model values and errors to evaluate reference points and calculate confidence intervals. In addition, the model accounts for the broader spatial distribution of scallop abundance.

The model included ten areas, comprising four large zones and six smaller scallop replenishment areas (SRAs). Figure 11 illustrates the areas defined for the stock model. The structure of standardised catch rates and related assessment data-inputs were monthly for either ten areas (separating the SRAs) or four zones (grouping each SRA into their larger zone).

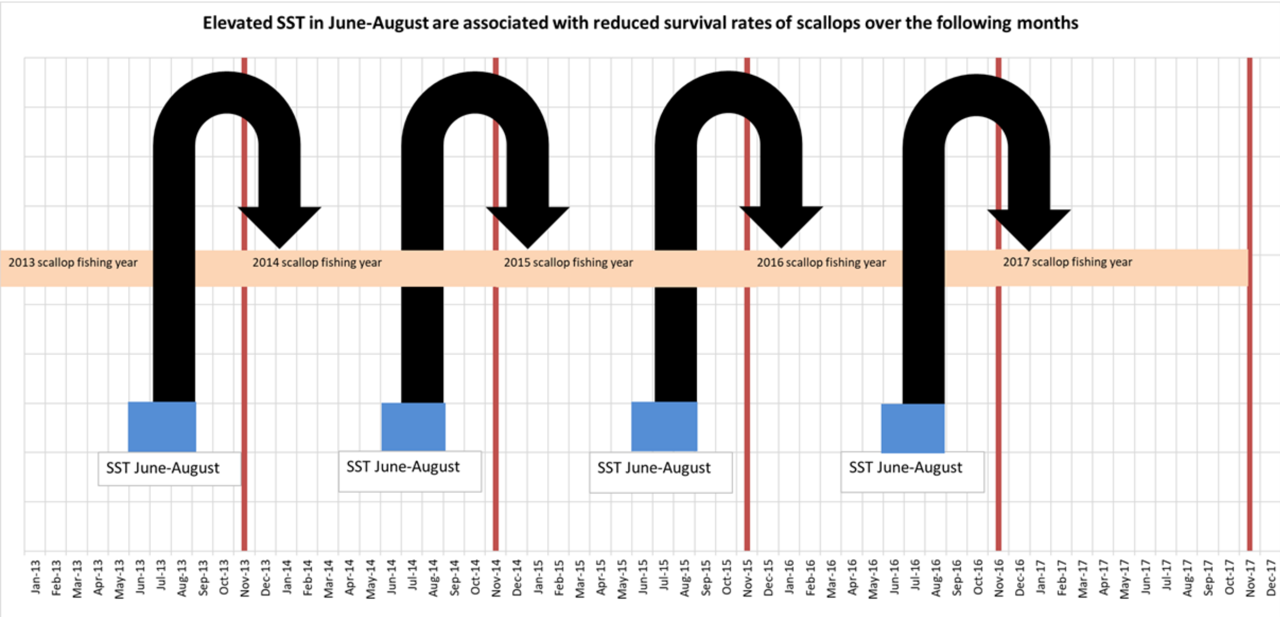

Figure 10. Example pattern of mean winter SST used to model natural mortality in the population dynamics.

The details of the population model are in Appendix 12.4 (from page 78; Table 28, Table 29 and Table 30). Normal negative log-likelihoods calibrated the model to data inputs and parameter settings (O'Neill et al., 2018); also see Table 30 for ADMB detail.

The model consisted of three elements:

1) process dynamics of scallop births, growth, and mortality (Table 28 in Appendix 12.4),
2) parameters for the dynamics (Table 29 in Appendix 12.4) and
3) objective functions for matching predictions to data (Table 30 and Table 31 in Appendix 12.4).

The process element was the core of the model and accounts for the dynamics of the population (fishery stock), as inferred by the estimated and fixed parameters. The objective function was the combination of negative log-likelihood functions and priors (or penalties). Importantly, the winter SST environmental factor was associated with natural mortality.

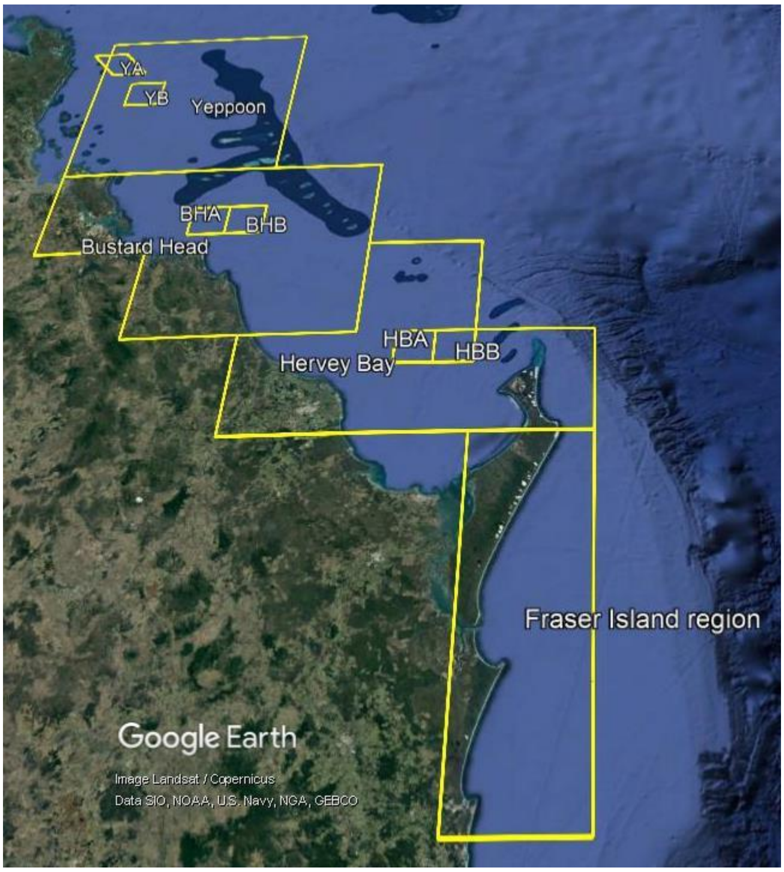

Figure 11. Ten areas for the scallop fishery from north to south: YA, YB, Yeppoon, BHA, BHB, Bustard Head, HBA, HBB, Hervey Bay and K'gari (Fraser Island) area. YA, YB, BHA, BHB, HBA and HBB were scallop replenishment areas (SRA).

The primary analyses considered two scenarios that exploited a mixture of both coarse and higher resolution spatial data. In both scenarios the four coarse zones were general Yeppoon (Yeppoon, YA, YB), general Bustard Head (Bustard Head, BHA, BHB), general Hervey Bay (Hervey Bay, HBA, HBB) and the K'gari (east Fraser Island) zone.

- Scenario 1:
    - The harvest data of the ten areas from fishing years 1956 to 2018.
    - The standardised catch rates of the four zones from fishing years 1978 to 2018.
- Scenario 2:
    - The harvest data of the ten areas from fishing years 1956 to 2018.
    - The standardised catch rates of the four zones from fishing years 1989 to 2018.

In addition, the annual means of winter SST from 1956 to 2018 were associated with natural mortality.

The sensitivity analyses were:

- Survey catch efficiency (s_{1+}) for 1+ scallop: 0.2, 0.3, and 0.4, instead of the base case of 0.6205.
- Four hierarchical optimisation procedures in ADMB (Table 20, Appendix 12.2).
- Five sets of initial values (Table 21, Appendix 12.2).

The sensitivity analysis for a scenario produced many different cases (3 catch efficiencies × 4 optimisation procedures × 5 sets of initial values × 2 effects with and without SST).

ADMB computer software optimisation and MCMC algorithms fitted the model to data, and quantified model parameter variances (Fournier et al., 2012).

The model estimation process in MATLAB® (MathWorks, 2020) consisted of a maximum likelihood (ML) step followed by Markov chain Monte Carlo sampling (MCMC); similar to ADMB. The flow of the estimation process is summarised in Figure 12. The maximum likelihood step used MATLAB global optimisation (MathWorks, 2020), 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 10 000 iterations of each parameter.

A customised 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; Gelman et al., 2004). The final parameter distributions were for 1000 posterior MCMC samples thinned from one solution stored per 100 samples. MCMC parameter traces and autocorrelations were assessed for convergence and independence (Plummer et al., 2006).

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 population model dynamics and parameters calculated fishery reference points in MATLAB. This was by optimising the dynamics using an average annual fishing mortality rate F, for each MCMC posterior parameter sample. The optimising was for the equilibrium reference points of B_{40}, B_{MSY}, B_{50} and B_{60} (see glossary). All parameter uncertainties were included except stochastic recruitment variation, which was set to one. The average fishing-mortality pattern for the years 2017–2018 split the annual F into monthly rates. The monthly fishing mortality rates were then converted into harvest rates, where the harvest rate was $u = 1 - exp(-F)$. The monthly harvest-rate u connected with equation 5, in Table 28 on page 78 (Appendix 12.4).

Model development and verification used three software packages ADMB, MATLAB® and R (Fournier et al., 2012; R Development Core Team, 2018; MathWorks, 2020). Model optimisations were only through ADMB and MATLAB. R supported ADMB data loading and graphical outputs.

Even though the population dynamics were the same in all software packages, there were subtle differences in the handling of some model aspects (Table 6). These differences were in:

- Negative log-likelihoods (Table 30 and Table 31, from page 82). The models covered different methods to penalise overly high harvest rates, and include minimum standard deviations in negative log-likelihoods.
- Catchability parameters. They were estimated in ADMB, and integrated out in MATLAB (Haddon, 2001).
- Hyper-parameters (Table 30). These additional parameters were set in ADMB. They were not in MATLAB.
- Estimated annual recruitment deviations. Their standard deviation was constrained within reasonable bounds in MATLAB (Table 31), and treated freely in ADMB.
- SST effects on natural mortality (M). ADMB used a logit link and MATLAB a logarithm form.

The differences in models, were not in the software itself, but in their settings. The different models labels/titles were 'spatial-M1' for the ten-area ADMB coding, 'spatial-M2' for the ten-area MATLAB coding, and 'non-spatial' for the zone-combined (region 3) analysis through MATLAB. The non-spatial ADMB coding had large recruitment deviations and annual jumps, and was not reported. However, the general time-series trend from this model was similar to others.

Table 6. Differences in the ADMB and MATLAB spatial-model operation and tuning.

Model aspect	**ADMB –spatial M1**	**MATLAB – spatial M2**	**References for method**
Negative log-likelihoods (-LL) for catch rates	$\frac{n}{2}(\log(2\pi) + 2\log(\sigma) + 1)$, no minimum standard deviation setting.	$\frac{n}{2}(\log(2\pi) + 2\log(\sigma) + (\hat{\sigma}/\sigma)^2)$, minimum standard deviation set based on LLM-REML estimates.	Haddon (2001) O'Neill et al. (2018)
Negative log-likelihoods for high harvest rates	Harvest rates constrained between 0 and 1 using a truncated normal equation 19, Table 30 on page 82.	Harvest rates penalised above 0.8, using a normal -LL, Table 31 on page 85.	Tanner (1996) for M1 Francis (2011) for M2
Catchability parameters for fitting catch rates	Estimated five parameters for fishery and survey 0+ catch rates, Table 29 on page 80.	The five parameters were closed-form median estimates of standardised catch rates divided by the midyear biomass. No direct estimated parameters.	Haddon (2001) O'Neill et al. (2018)
Hyper-parameters	Eight parameters for vague prior distributions. They were user-set large standard deviations.	Not required.	Fournier et al. (2012) for ADMB.
Annual recruitment deviations	Unconstrained and allowed large deviations. 31 parameters for 1988–2018. Vague prior normal distribution. Mean of distribution was nonzero.	Constrained. 30 (n-1) parameters for 1988–2018. Penalised normal –LL for standard deviations above 0.2. See the –LL form above in row 1. Mean of distribution was zero.	O'Neill et al. (2014) and Courtney et al. (2014) for M2.
Natural mortality M	Logit link for estimated SST effect.	Log linear equation for estimated SST effect.	McCullagh and Nelder (1989)
Number of estimated parameters	51	45	

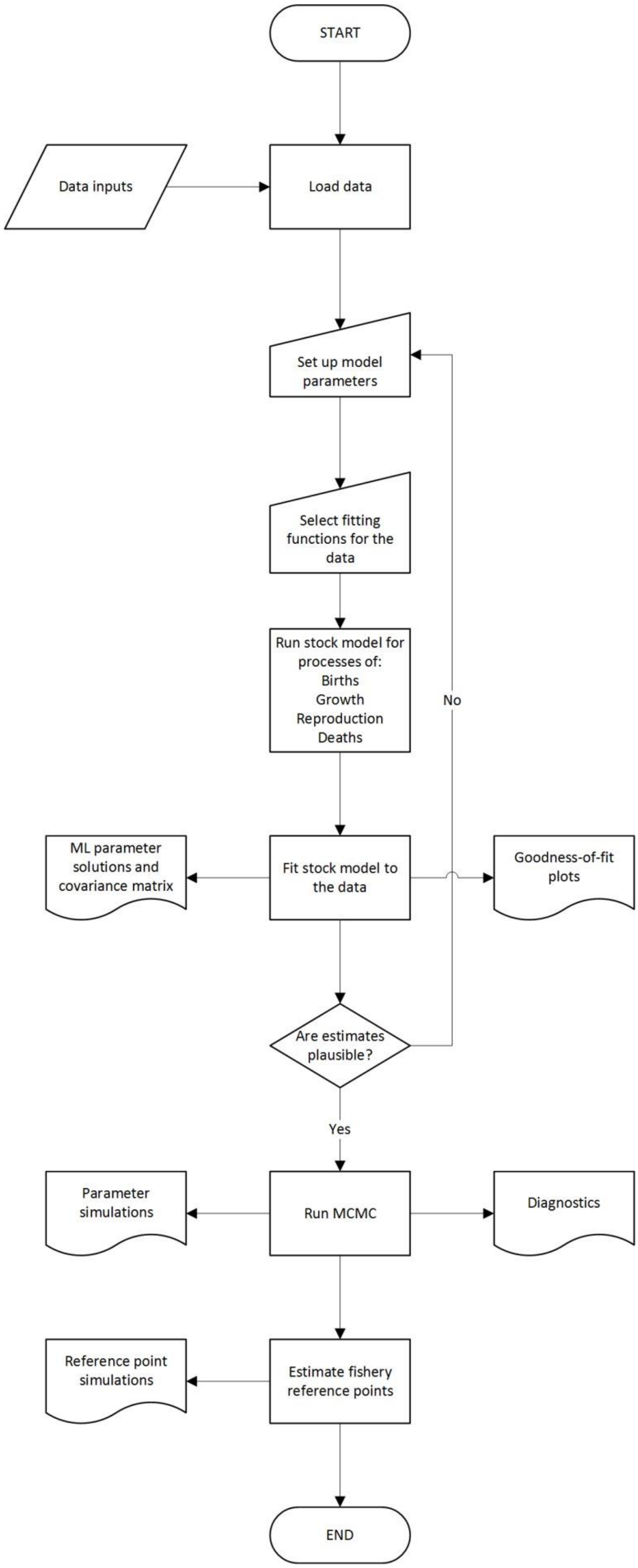

Figure 12. Flow of operations for the stock model from loading the data to evaluating model predictions.

3.4.2 Model projections

Hypothetical scenarios projected future fishing in the stock models. The projection methods were simple expectations based on the data and maximum likelihood parameter estimates (Richards et al., 1998).

The non-spatial model, for region 3 with no temperature effect and 1977–2018 catch rates, projected 20 years into the future under the following assumptions:

- The fishing effort (harvest rate) pattern was modelled using two scenarios: either 1) as it was in 2017 and 2018 (open six months of the year, with SRAs closed all year round), or 2) a new proposed four-month scenario (open December, January, March and April, with SRAs closed). Discussions between fishery management and industry indicated a preference for the four-month scenario.
- The maximum likelihood parameter estimates defined the forward predictions, with deterministic recruitment according to the Beverton-Holt function and constant M = 0.09 per month.
- Various levels of fishing effort were set for the future (Table 7). The model predicted spawning biomass, harvest and catch rates until 2038 (20 years forward).
- The model projections determined the number of years for spawning stock (spawning egg production, labelled E) to recover to 40% of virgin (E_{40}), 45% (E_{45}), 50% (E_{50}), and 60% (E_{60}) under the two patterns of fishing effort (six-month fishery or four-month fishery).

Table 7. Levels of fishing for the forward projection model.

Boat-days	0	215	858	1502	2145	2243	5000
Effort units	0	11825	47190	82610	118000	123365	275000
Description	No fishing	10% of 2145 days	40% of 2145 days	70% of 2145 days	Status quo proposal	MSY	Higher example

The spatial-M2 model, with SST effect and 1977–2018 catch rates had the following 20-year projection assumptions:

- The fishing effort pattern was the same as above.
- Recruitment deviations used for the forward projections were guided by historical (1999–2018) estimates.
- There were two temperature settings to vary natural mortality rate (*M*): the average temperature from 1950–1956 (past SST), and the last 20 years of temperature (current SST).
- The maximum likelihood parameters defined the forward predictions.
- Levels of fishing effort were set as in Table 7, and the model predicted spawning biomass until 2038 (20 years forward).

The scallop stock model used information from various sources to predict the spawning stock biomass and other indicators, and reference points. The data sources are in Table 8. Environmental data were from publicly available monitoring programs, such as NOAA (National Oceanic and Atmospheric Administration – US science agency) and eReefs (https://ereefs.org.au/ereefs).

Table 8. List of data for project analyses and the population model.

Data name	Time	Space	Units	Source
Historical catch	1977 to 1988 (annually)	None	Weights (kg)	Dredge *et al*. (2016)
CFISH catch*	Jan 1988 to Oct 2018 (monthly)	30 x 30 minutes	Baskets	DAF
VMS catch**	Jan 2000 to Oct 2018 (monthly)	0.6 x 0.6 minutes	Weights (kg)	DAF
VMS effort**	Jan 2000 to Oct 2018 (monthly)	0.6 x 0.6 minutes	Hours	DAF
VMS CPUE**	Jan 2000 to Oct 2018 (monthly)	0.6 x 0.6 minutes	Weights kg per hour	DAF
Standardised catch rates	Jan 1988 to Oct 2018 (monthly)	4 zones and 10 areas	Baskets per boat-day	DAF
Density	Every October from 1997 to 2006 and 2017 to 2018	Point-referenced (longitude, latitude)	Numbers per hectare	DAF
Sea surface temperature (SST)	Apr 2002 to Oct 2018 (monthly)	1.2 x 1.2 minutes	Celsius (°C)	eReefs
Chlorophyll a (Chl-a)	Jul 2002 to Oct 2018 (monthly)	0.6 x 0.6 minutes	Mg/m^3	eReefs
SST	1 Sept 1981 to Oct 2018 (daily)	15.0 x 15.0 minutes	Celsius (°C)	NOAA OISST
SST	Jan 1854 to Oct 2018 (monthly)	2.0 x 2.0 degrees	Celsius (°C)	NOAA ERSST v5
Winds	1978 to 2018	Latitude – daily mean	km $hour^{-1}$ and degrees	BOM
Lunar	1978 to 2018	N/A	Luminance	DAF
Fishing power	1978 to 2018	N/A	Per boat	DAF

* The mandatory CFISH logbook data, ** Vessel monitoring system data

3.4.3 Model scenarios

A number of scenarios (i.e. data and model settings) were analysed that exploited a mixture of both four-zone and ten-area spatial data. There were many investigations, including:

- Spatial ten-area or non-spatial models.
- Harvest data from all ten areas (Figure 42, left map on page 70) for fishing years 1956 to 2018, or combined across zones for the proposed management region 3 (Figure 3, page 3).
- Standardised catch rates were for four zones (Figure 43) from fishing years 1978 to 2018, or from fishing years 1989 to 2018, or combined across zones for the proposed management region 3.
- The annual means of winter SST were associated with natural mortality (*M*).
- Survey catch efficiency $^{(s1+)}$ for 1+ aged scallop, for the proportion values of 0.2, 0.3, and 0.4. The catchability value of 0.6205 from Joll and Penn (1990) was tested, but model fits generally overestimated these adjusted densities. Lower catchability 0.2–0.4 improved model fits, and aligned closer to values from Miller et al. (2019).
- Optimisation procedures and initial model parameter values.

The different models labels/titles were '**spatial-M1**' for the ten-area ADMB analysis, '**spatial-M2**' for the ten-area MATLAB analysis, and '**non-spatial**' for the zone-combined (region 3) analysis through MATLAB. Table 6, on page 23 and above, listed the method differences.

The modelling of scallop natural mortalities was set around the mean of 8.6% per month (Dredge, 1985). From the mean, spatial-M1 estimated natural mortality varied around 7–15% per month for 1977–2018 catch rates, and 7–13% for 1988–2018 catch rates. For the log linear form in spatial-M2, natural mortality varied between 7–12% per month.

3.4.4 The previous model by Campbell et al. (2012)

Previous stock assessments have used the age-based dynamic population model described in Campbell et al. (2012), which was conditioned by fishing effort rather than by harvest (Campbell et al., 2012; Yang et al., 2016). Estimates from the previous Campbell et al. (2012) model were compared to the models developed in this study.

The previous model was based on monthly age-based dynamics, and allowed for more complexity than the new model. The Campbell et al. model contained different statistical weightings of data components, incomplete data structures, spatial patterns of scallop aggregations and their catchability, and 41 spatial areas. The model can allow for variable changes in spatial-temporal recruitment, ability for fishers to exploit high-density areas, and history of fishery management. The Campbell et al model treated fishing year 1977 as the virgin stock reference year (i.e. earlier 1956–1976 data was not included) and included the K'gari (Fraser Island) zone (i.e. data from all four zones). The Campbell model did not include temperature effects, and used the zone combined catch rate index. In addition, the Campbell model only used the zero-plus (0+ age group) survey data as a recruitment index, and not the survey 1+ data.

The Campbell et al. (2012) model also had nearly twice the number of model parameters of the newer model design herein. The Campbell model had 95 parameters (listed in the original report) whereas the new model had 51 parameters (listed in Table 29). The full 95 parameters were difficult to estimate within the ADMB framework, which was a reason to investigate new, simpler models.

Two scenarios were fitted in the Campbell et al. (2012) model: the catch rates of fishing years 1978–2018 (called M1); and the catch rates of fishing years 1989–2018 (called M3). The labels M1 and M3 were for consistency with the 2016 stock assessment (Table 3-3, Yang et al., 2016).

ADMB computer software optimisation and MCMC algorithms fitted the model to data, and quantified model parameter variances (Fournier et al., 2012).

4 Results

4.1 Harvests and catch rates

4.1.1 Harvests

Scallop harvests by month from the period 1956–2018 are in Figure 13. The figure shows that scallop harvest follows a typical seasonal change. Harvests were low before 1969. Harvests built to highs around 1993, and steadily decreased thereafter. Harvests were generally higher from November to March, and were low in 2014–2017.

In each fishing year, maximum harvest generally occurred in early summer months when young scallops were recruited into the fishery (Williams and Dredge, 1981). The seasonal pattern changed in later years, with most scallops harvested between November and January (Figure 14). In the last five years (2013–2018), 70–85% of the annual harvest taken was between November and January. Harvests in the months after were small compared to early years.

The increased harvest of November–January scallop (Figure 14) were likely attributed to the November opening of the fishery and January opening of SRAs. High fishing pressure during November–January increasingly appeared in stock assessment results, particularly for January.

Figure 15 shows the annual decline in harvests by zone across the fishery. Before 2002, harvests were normally ≥ 800 t of meat weight per fishing year, and peaked in 1993 at over 1800 t. Since 2011, annual harvests were mostly ≤ 400 t. Declines were notable in all zones. Harvests from east K'gari waters were sporadic; they increased in 2013 and 2018, with a rough 4–5 year cycle between good harvest years.

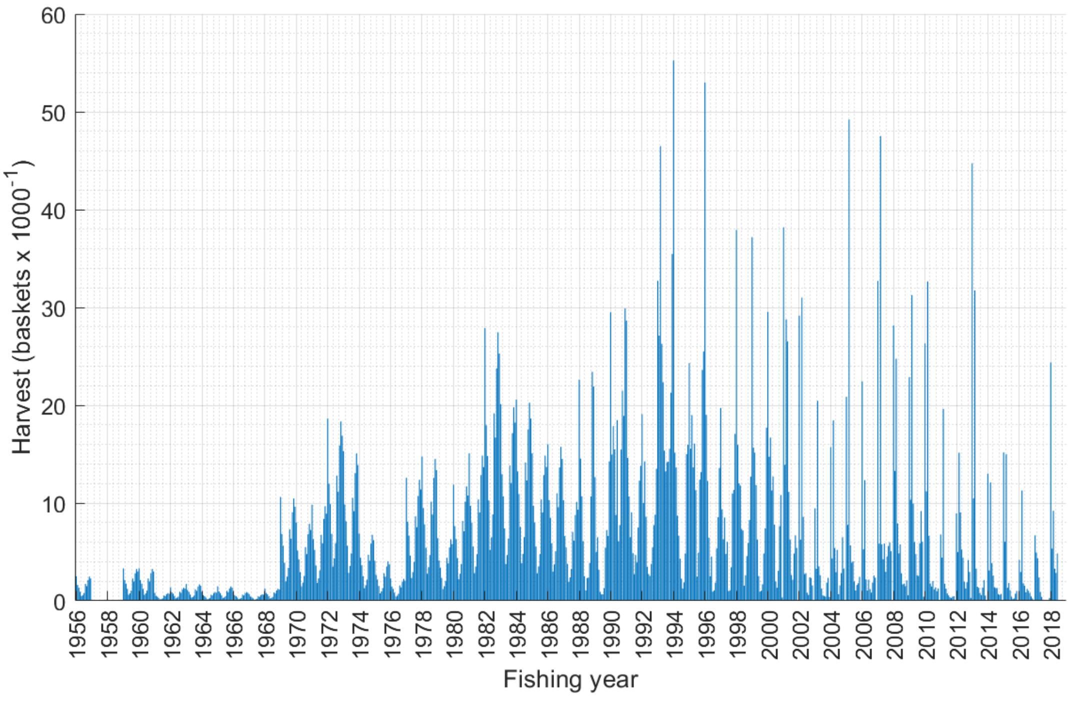

Figure 13. Monthly scallop harvests, from waters between 22.5° S and 27.0° S latitudes along the east coast of Queensland. Since 2002, clear spikes in harvest occurred in the months of November and January.

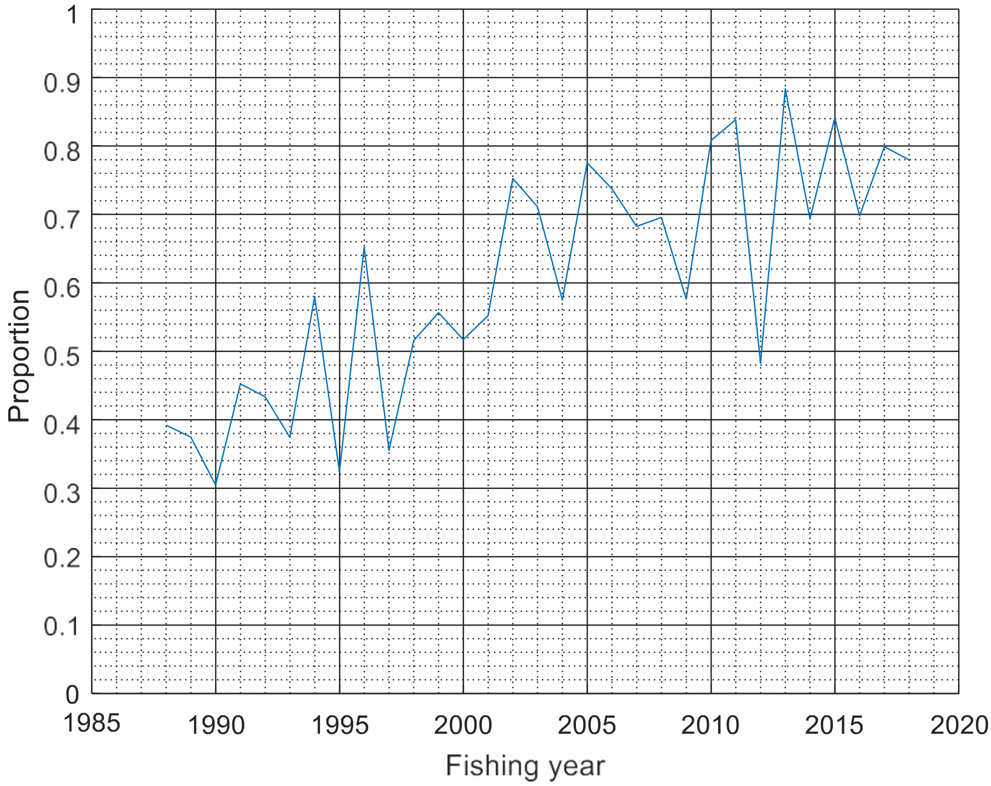

Figure 14. Proportion of annual harvest taken between November and January each fishing year 1988–2018.

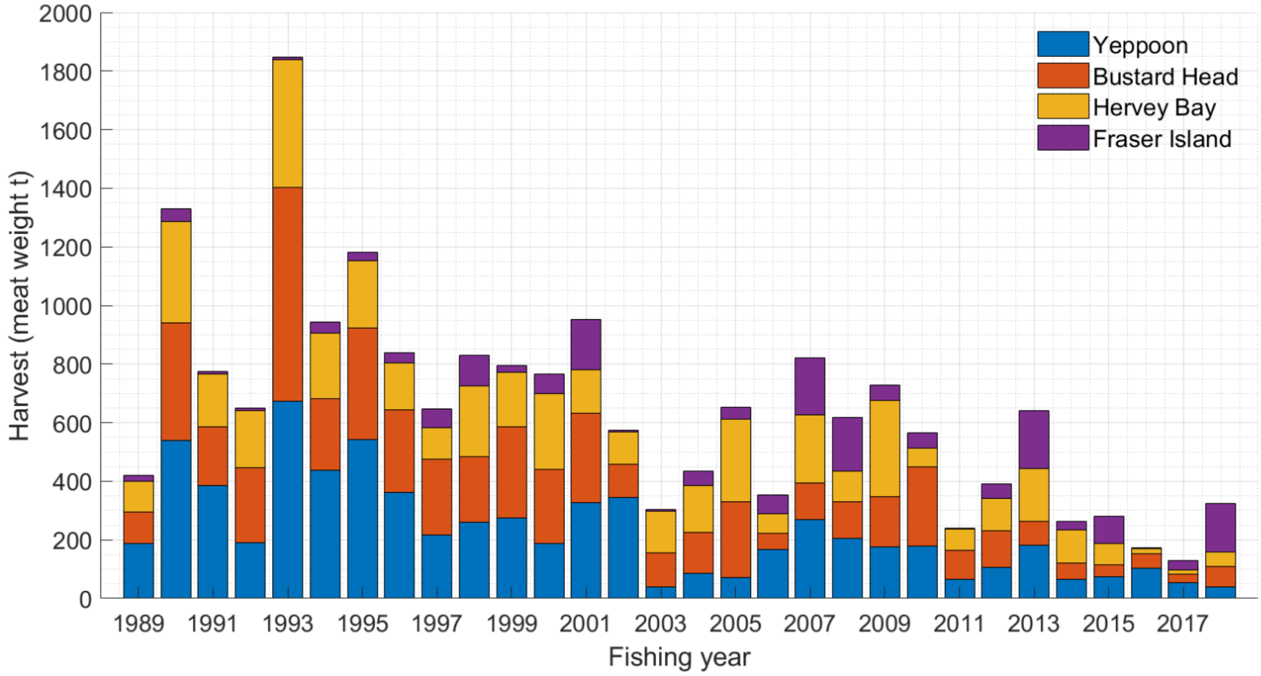

Figure 15. Annual scallop harvest in meat weight (tonnes).

Inspection of scallop harvests by fishing month and area showed strong spikes of high harvest (Figure 16).

Since 2001, the opening of SRAs in January have produced high harvests for only a month, with little thereafter (Figure 16). January fishing in the small SRAs was generally crowded. Vessel numbers typically ranged 20–40 per SRA per month, and the maximum number was 69 vessels in HBA for January 2009. From February onwards, vessel numbers dropped typically to less than 10 per SRA per month. Fishing in the SRAs generally yielded 30% (range 14–50%) of annual scallop harvest.

For the larger zones of Yeppoon, Bustard Head and Hervey Bay, outside of the SRAs (Figure 42 map, on page 70 in Appendix 12.1), monthly harvests tended to be highest from November to February (Figure 16). Vessel numbers typically ranged 10–40 per large non-SRA area per month, during November to February, and less than 10 for the remainder of the fishing year.

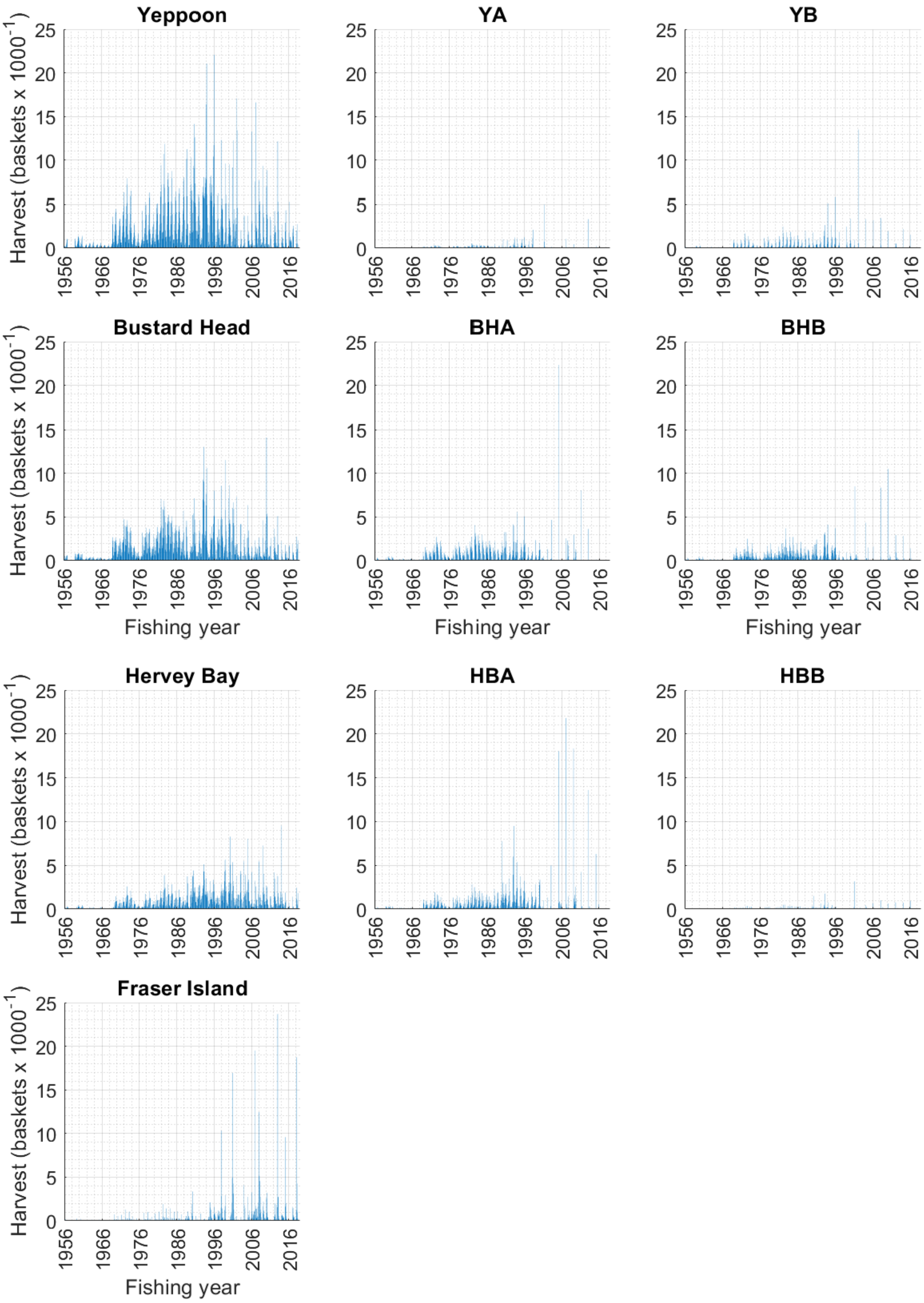

Figure 16. Monthly scallop harvest by ten areas, Yeppoon, YA (Yeppoon SRA A), YB (Yeppoon SRA B), Bustard Head, BHA (Bustard Head SRA A), BHB (Bustard Head SRA B), Hervey Bay, HBA (Hervey Bay SRA A), HBB (Hervey Bay SRA B), and K'gari (Fraser Island).

4.1.2 Catch rates

Analysis 1: 1988–2018 for Yeppoon, Bustard Head, Hervey Bay and K'gari

The catch rates for 1988–2018 for Yeppoon, Bustard Head and Hervey Bay showed late improvement in March 2018, around 15 baskets (Figure 17). Catch rates were still low for November 2017 and January 2018, compared to early years, but improved on 2016–2017. The highest catch rate in these areas was 56 baskets from Yeppoon, 49 baskets from Bustard Head, and 46 baskets from Hervey Bay. Notable lows, signalling failed recruitment, were in 1997 and 2016–2017. Catch rates in K'gari were sporadic, with catch rates only higher than 55 baskets per boat-day on four occasions in 31 years. K'gari catch rates did show recovery in 2018.

The 95% confidence intervals on mean catch rates were about ±3 baskets per boat-day (relative standard error, RSE, of 15%) for all zones (Figure 17).

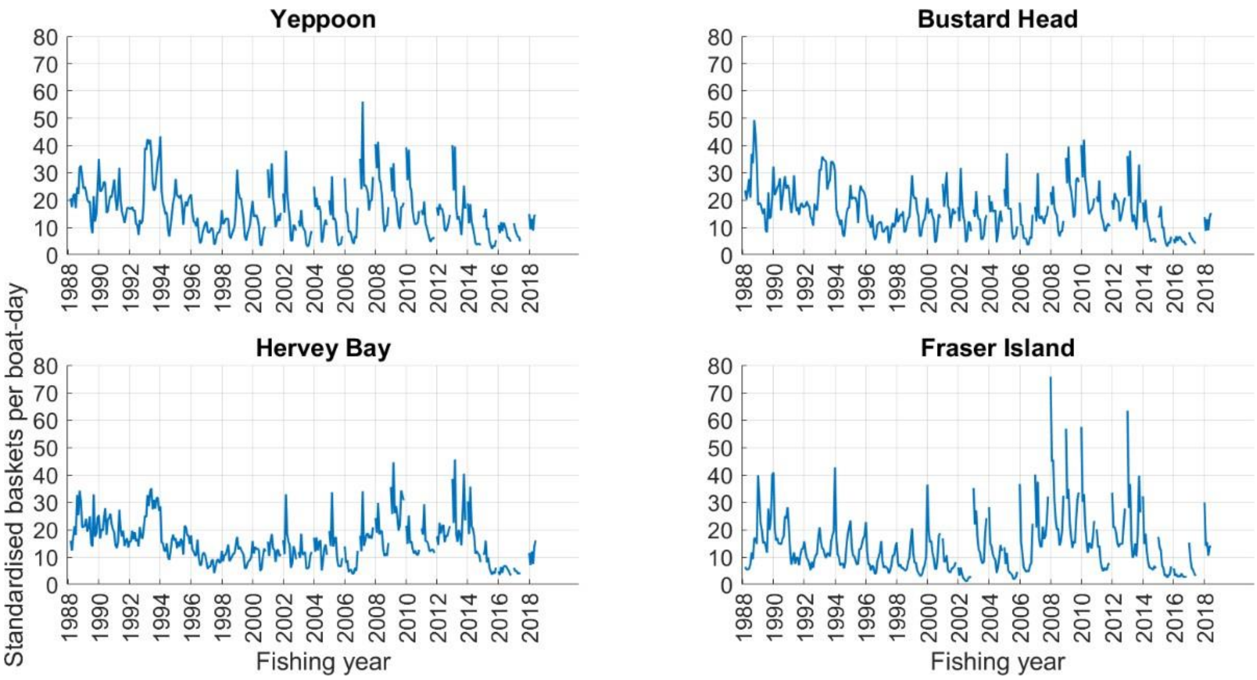

Figure 17. Standardised monthly mean catch rates of scallop for four zones, with SRAs included from 1988–2018. Breaks in the time series after 2000 represent the southern temporal closure from 20 September to 1 November annually. Additional closures for scallop fishing covered April–October 2017 and April–October 2018.

Analysis 2: 1977–2018 for Yeppoon, Bustard Head, Hervey Bay and K'gari

The trend in long-term mean catch rates showed a marked contrast between pre- and post-1988 (Figure 18). The contrast of the 2016–2017 decline against the time series was, like in 1997, alarming. These low catch-rate years appeared to signal low recruitment and limited stock to support fishery income and profit. In terms of reference point management and harvest strategies, settings need to help avoid these events from occurring.

For pre-1988 fishing years, catch rates in Yeppoon, Bustard Head and Hervey Bay started relatively high from 1977–1978, declined in 1979–1982, spiked in 1983, and declined again in 1984–1988. The spikes in catch rates in 1983 were from observations of around only 5 boat-days per month for Yeppoon, 1 boat-day per month for Bustard Head, and 11 boat-days per month for Hervey Bay. Catches east of K'gari pre–1988 were infrequent. The highest monthly catch rates pre-1988 exceeded 200 baskets per boat-day in Yeppoon, Bustard Head and Hervey Bay and exceeded 350 baskets per boat-day in K'gari. Post 1988, trends in catch rates were generally less than 30 baskets.

For comparing means on Figure 18, the 95% confidence intervals on catch rates were in the range of ± 14–28 baskets (RSE 17–47%) pre-1988 and ± 3 baskets (RSE 15%) thereafter for Yeppoon, Bustard Head and Hervey Bay. They were ± 29–92 baskets (RSE ≥ 72%) pre-1988 and ± 3 baskets (RSE 15%) thereafter for K'gari.

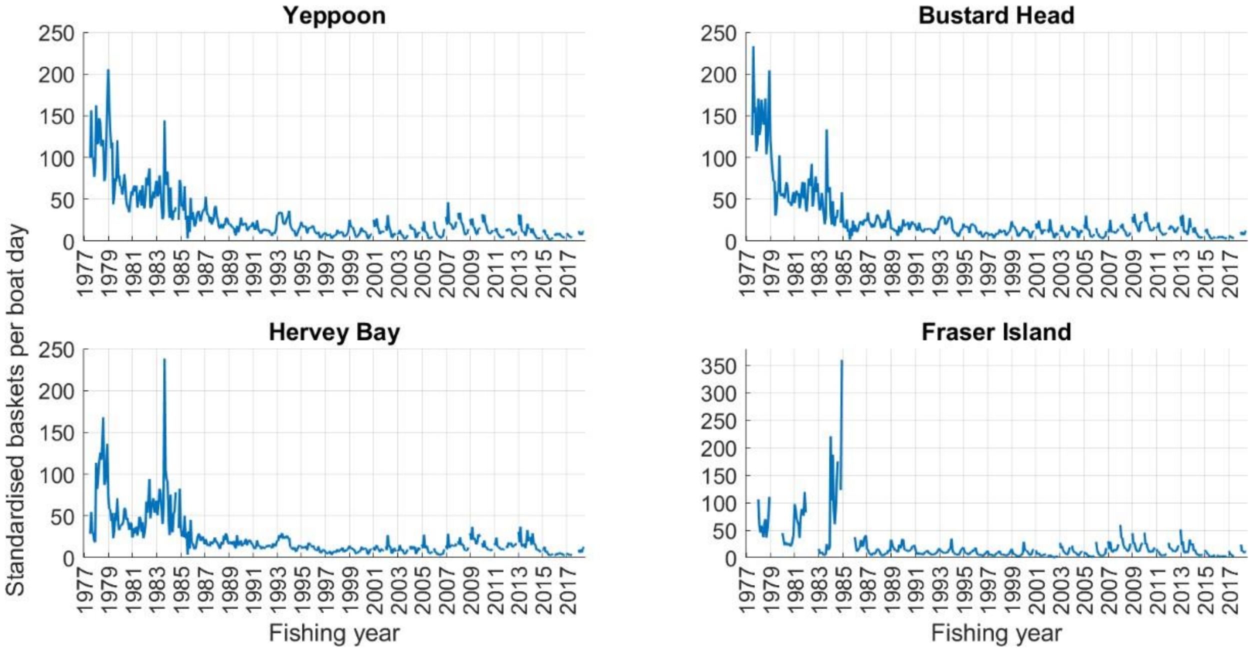

Figure 18. Standardised monthly catch rates of scallop for 1977–2018, with SRAs included.

<u>Analysis 3: 1988–2018, proposed management region 3 (i.e. excluding K'gari)</u>

Figure 19 shows that region 3 catch rates improved in 2018, up to 20 baskets from the 2016–2017 lows. This improvement was for March and April 2018. However, despite the improvement, catch rates were still low for the previous normal-recruitment months of November 2017 and January 2018. The March and April 2018 improvement may signal a late cohort recruiting to the fishery in the Yeppoon and Bustard Head zones. This was a positive signal for the fishery, but it may only reflect an aggregated pattern of fishing. To improve understanding of scallop abundance, information on 2019–2020 catch rates need to verify increases.

The 95% confidence intervals on mean catch rates were about ±3 baskets per boat-day, with an RSE of 15% (Figure 19).

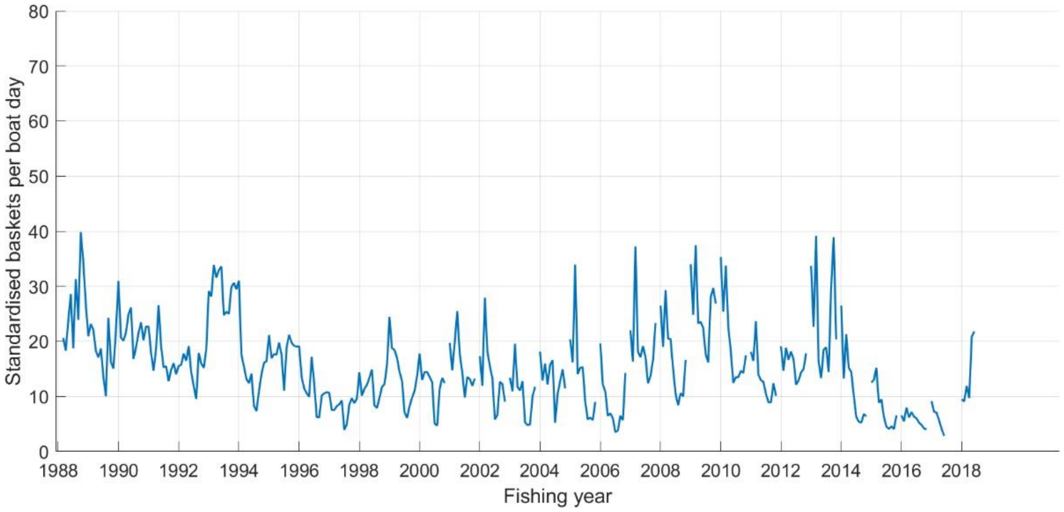

Figure 19. Standardised monthly catch rates 1988–2018 for the proposed management region 3 (i.e. excluding K'gari). Breaks in the time series represent the southern temporal closure from 20 September to 1 November and whole fishery closures for April–October 2017 and April–October 2018.

Analysis 4: 1977–2018, proposed management region 3 (i.e. excluding K'gari)

The trend in long-term predicted mean catch rates showed a marked contrast between pre- and post-1988 (Figure 20). The trend in catch rates followed the same pattern as the trend in catch rates for the separate zones of Yeppoon, Bustard Head and Hervey Bay in Figure 18. For comparing means, the 95% confidence intervals on catch rates were generally in the range: ± 14–21 baskets (RSE 20–30%) pre-1988 and ± 3 baskets (RSE 15%) thereafter.

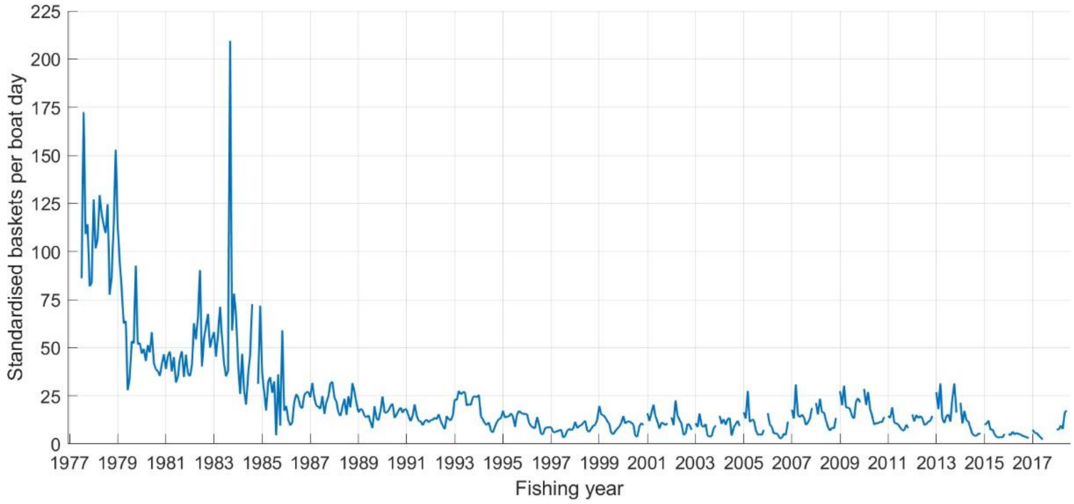

Figure 20. Standardised monthly catch rates 1977–2018 for the proposed management region 3(i.e. excluding K'gari).

For all analyses, there were no concerning residual patterns (see diagnostic plots, in Appendix 12.5 after page 86). Generally, the histograms of standardised residuals were normal in shape, and the scatter plots showed no pattern. Figure 47 to Figure 50 illustrated some outlying data with residuals in excess of -3 and +3. These residuals were few in comparison to the number of data, and their occurrence typical for logbook data.

4.2 Environmental correlations

Initial analyses focused on two variables, sea surface temperature (SST) and chlorophyll (Chl-a), to measure associations with November catch rates of scallops from 2002 to 2016. Above average SST was negatively associated with catch rates (Figure 21). Associations with Chl-a were inconsistent (Figure 22), and less apparent compared to earlier analyses by Courtney et al. (2015). The weak Chl-a relationship indicates no direct effect on scallop reproduction dynamics.

Figure 21 and Figure 22 show the estimates of associations (β) by space and temporal lags. The results illustrated associations where the 95% confidence intervals did not cover zero (i.e. statistically significant slopes/correlations). The results focused on the scallop fishery domain.

Temperature results, illustrated by the predominant blue colour, were indicative of a negative relationship between the November catch rates and SST for several time lags (Figure 21). This was generally more notable for SST during the preceding winter-spawning months. The result suggested above average winter SSTs might affect scallop survival.

November catch rate associations with Chl-a were less obvious and spatially confined (Figure 22). Results were unremarkable with marginal negative (green/blue colour) or positive (red/orange colour) estimates identified depending on the latitude and time lag. Any influence of Chl-a on catch rates was not obvious, and less than SST.

Additional analyses extended information on associations between scallop catch rates and SST from 1988 to 2017. Figure 23 presents the fishery wide correlations between November, December and January catch rates, and SST. The results indicated that higher temperatures might lower catch rates. More specifically, higher winter SSTs (June–August) were negatively associated with November–January catch rates.

Given this result, the population model tested the long-time series of winter SST (Figure 24). Figure 23 shows the predicted winter SST for the scallop fishery from the linear regression model in which the OISST winter SST data were regressed on the ERSSTv5 winter SST data ($R^2 = 0.6043$). The mean winter SST increased since the 1970s and varied between 20 and 22 °C. The population model setup was for a linear relationship between annual changes in natural mortality (M) and for annual mean winter SSTs; illustrated in Figure 24. The results are in the report section for population model estimates on page 44. Reasons for examining a natural mortality relationship, rather than a recruitment association, were to:

- Explain declines in the Queensland fishery and catch rates. Scallops can sometimes live for around four years, and catch rates of legal sized scallop consist of multiple age groups. Therefore, the winter SST associations noted above, may have resulted from enduring natural mortality affects rather than annual recruitment affects alone.
- Examine natural mortality affects separate from the annual recruitment deviations estimated by the model. Past modelling of environmental covariates affecting annual recruitment produced mixed results (Courtney et al., 2015; Madden, 2016); as described in the report introduction.
- Consider past findings of high temperature mortalities on Western Australian (WA) scallops, which affected all sized scallops and not just young recruits (Kangas et al., 2007; Caputi et al., 2014; Caputi et al., 2016). The WA studies showed negative correlation between SST in the preceding months with a November survey 0+ recruit-index. Generally, SST from the preceding December–January had the stronger correlation. However, elevated SST during the preceding winter spawning period April–June also had a significant negative correlation with the 0+ recruit-index. From the WA studies/papers, no specific SST effects described scallop recruitment or survival, but their papers gave the general impression that high SST reduced overall survival of scallops. Of note was that the main SST period identified by WA researchers was a longer lag (a 10-11 month lag effect for 0+) than herein for Queensland (4–5 month lag effect on legal sized 1+ aged scallops).

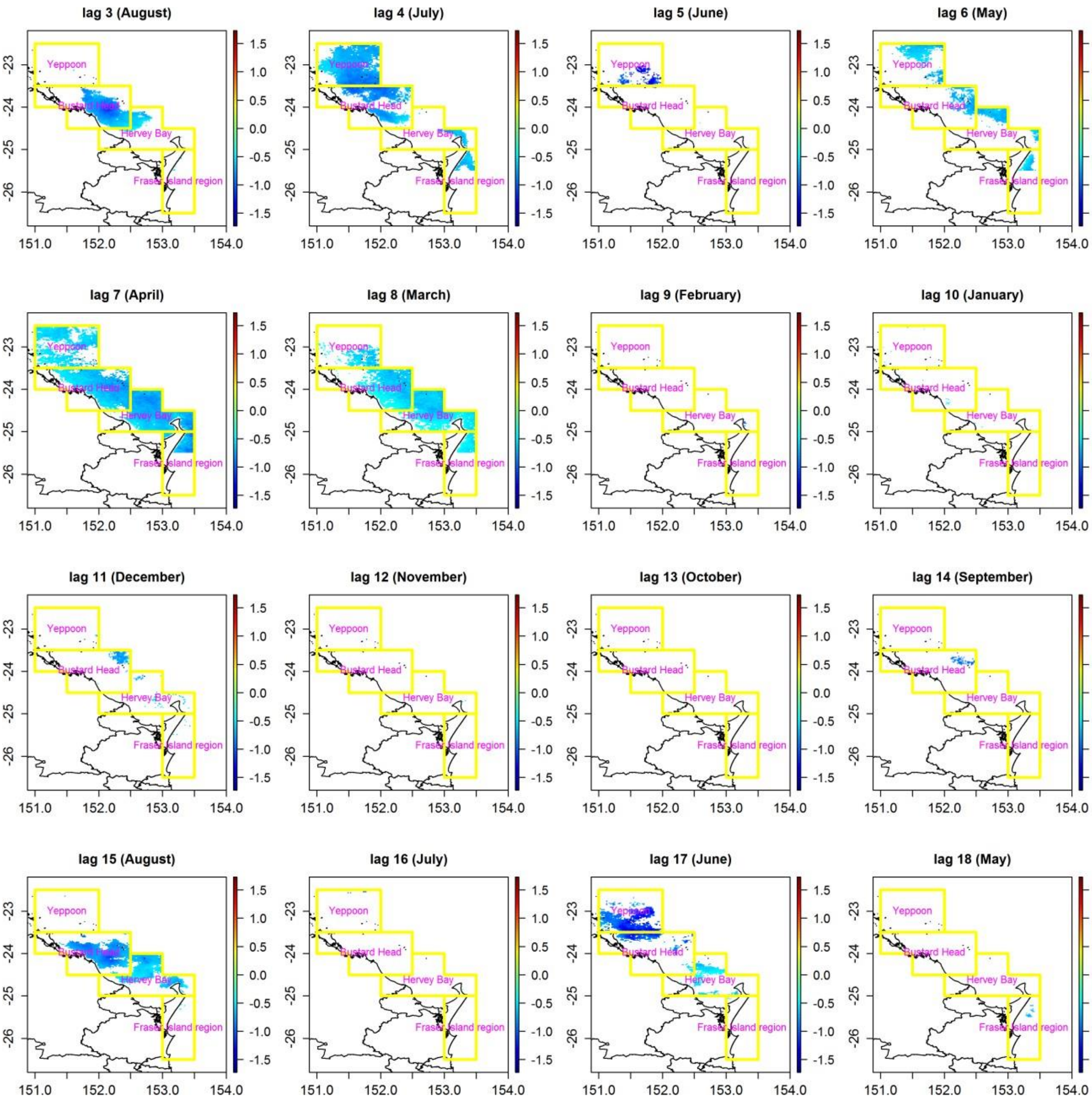

Figure 21. The posterior means of $\beta_{s,}$ in the case of SST against the November standardised catch rates for the whole fishery. The figure only illustrates results with 95% confidence intervals not covering zero. X- and y-axis of each plot expressed longitude and latitude, respectively. $\beta_{s,}$ measured the correlation, with one unit change of SST altered November standardised catch rates by $exp(\beta_{s,t})$. Data were for November catch rates and SST April 2002 to November 2016. The predominant blue colour was indicative of a negative relationship between the November catch rates and SST for several lags.

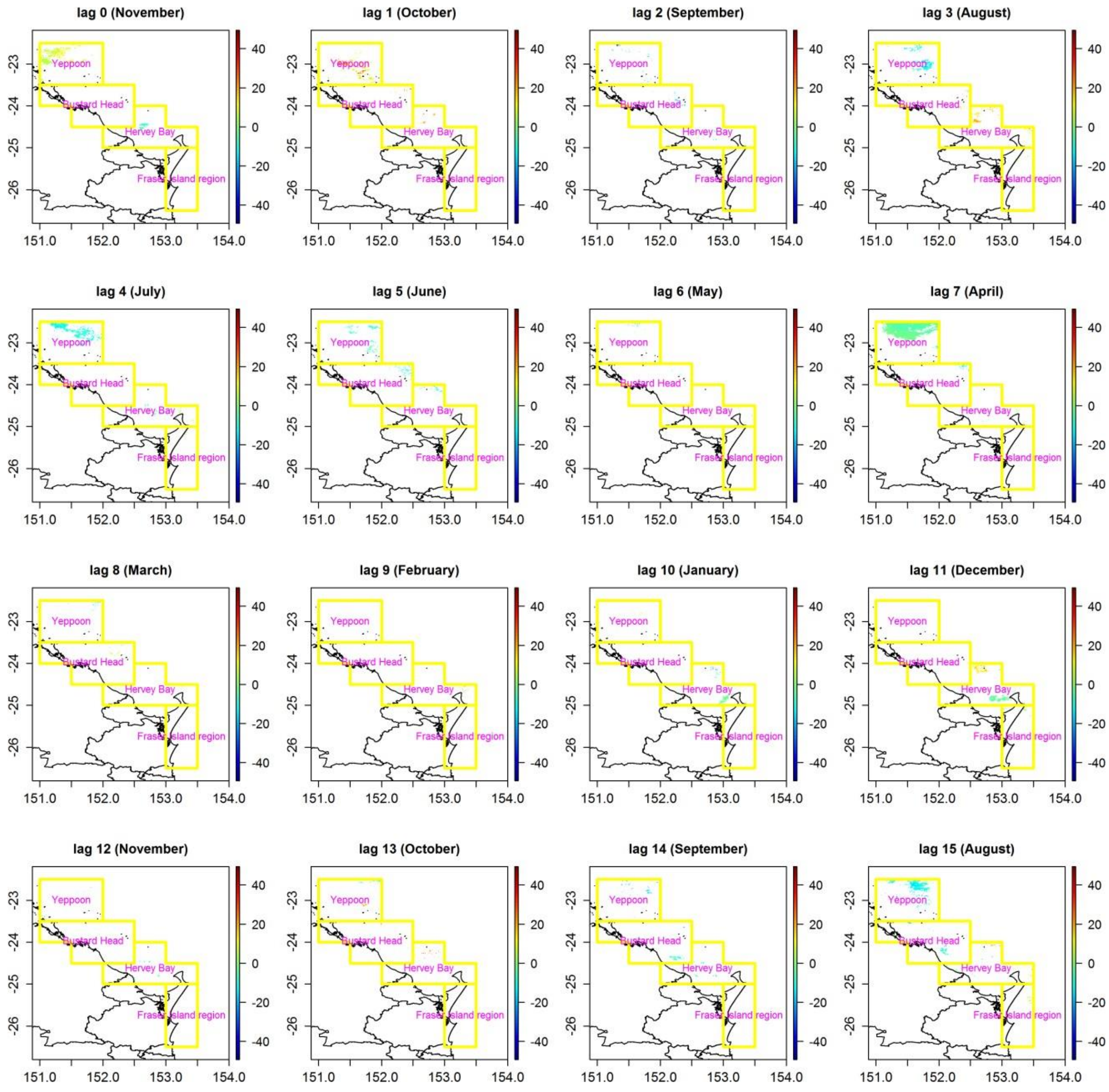

Figure 22. The posterior means of $\beta_{s,}$ in the case of Chl-a against November standardised catch rates for the whole fishery. The figure only illustrates results with 95% confidence intervals not covering zero. X- and y-axis of each plot expressed longitude and latitude, respectively. $\beta_{s,}$ measured the correlation, with one unit change of Chl-a altered November standardised catch rates by $exp(\beta_{s,t})$. Data were for November catch rates and Chl-a from April 2002 to November 2016The blue/green colours were indicative of negative relationships between the November standardised catch rates and Chl-a.

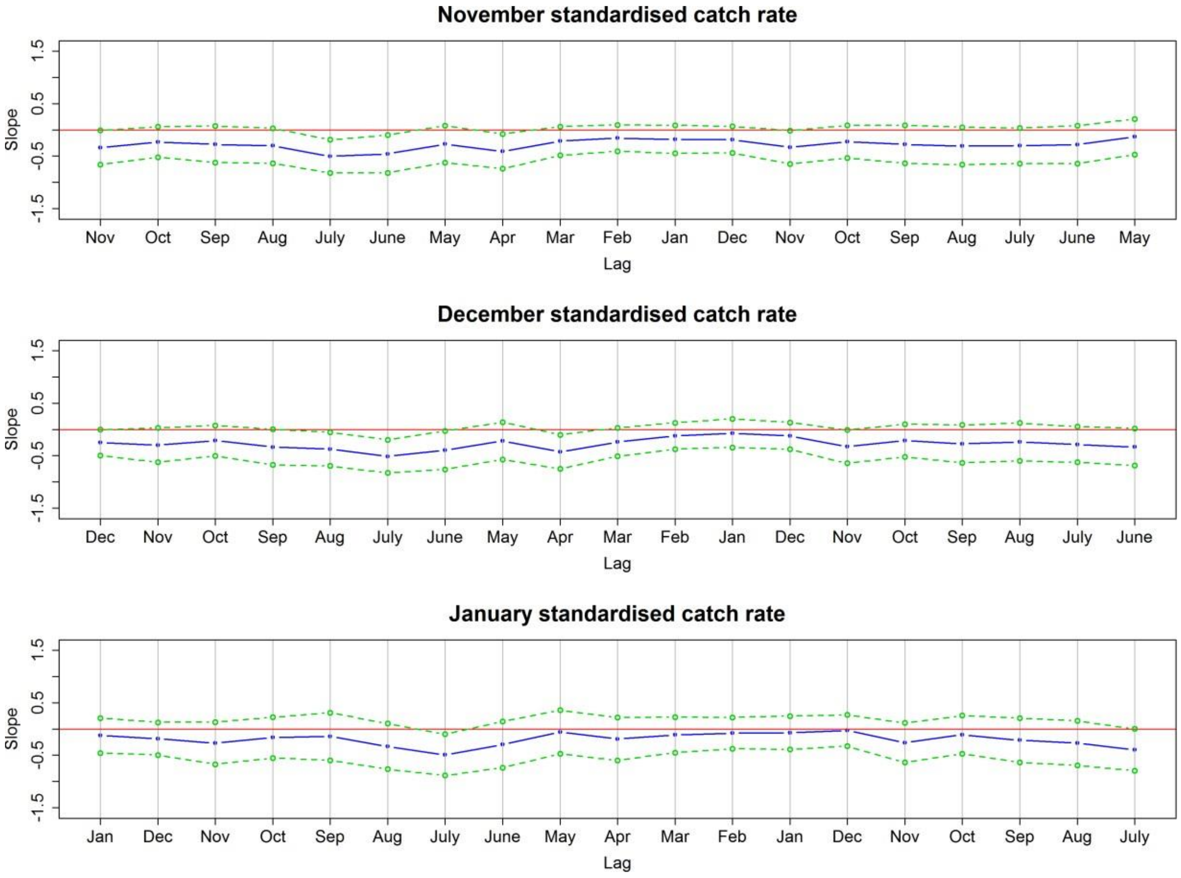

Figure 23. Correlation measures (β_t log parameter estimates) between monthly SST and November to January catch rates of scallops Jan 1988 – Jan 2018.

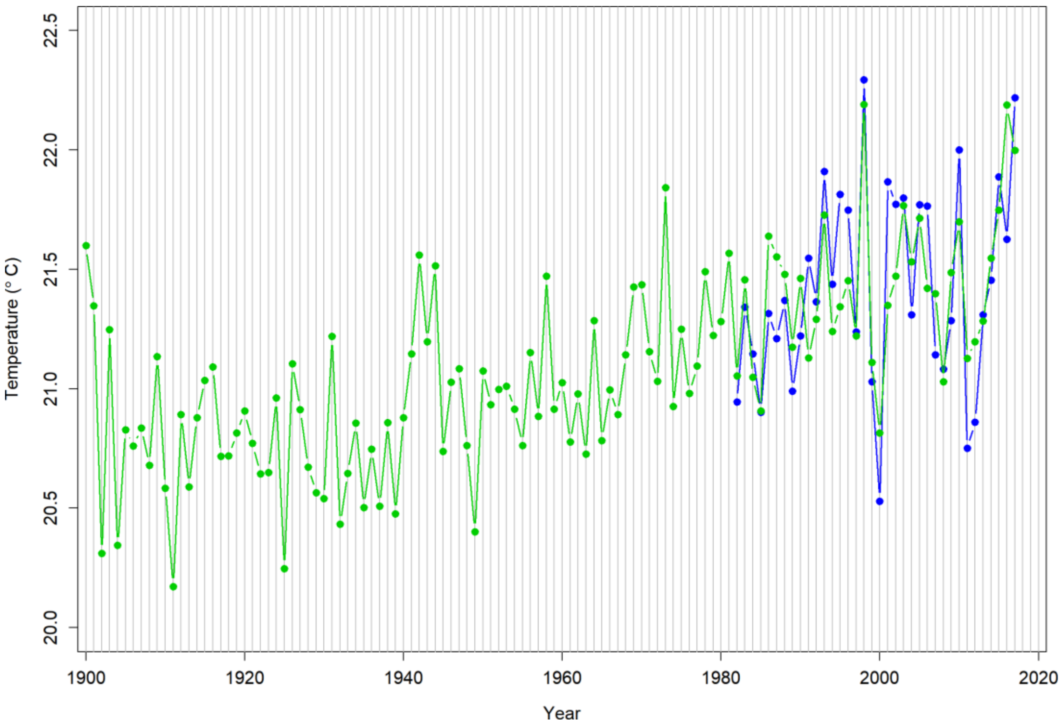

Figure 24. The estimated mean winter sea surface temperature (June–August SST) from OISST (blue line) and ERSSTv5 (green line) NOAA databases.

4.3 Population indicators

4.3.1 Survey estimates

Fishery-independent trawl surveys provided estimates of scallop densities (numbers per hectare) in October for years 1997–2006, and 2017–2018 (Table 9). In addition to scale densities to the broader area of commercial scallop fishing, TrackMapper outlined the areas fished (footprint) for all VMS data 2000–2018, including all six SRAs (Figure 25). The hectare estimates for Figure 25 are in Table 9.

Resulting estimates of scallop densities varied between areas and surveys (Table 9). The following summary provides key results, with the caveat of some confounding between changes in survey estimates and survey error. Note that the observed trawl densities were 38% lower than the catchability adjusted values in Table 9 and Table 10.

For young scallops, adjusted measures of recruitment aged < 1+ years in Table 9a, the surveys indicated:

- In 2018, low densities of scallops ≤ 20 per hectare for the zones of Yeppoon, Bustard Head and Hervey Bay.
- Densities were higher near 60 scallops per hectare for the K'gari zone in 2018, compared to less than 20 per hectare in 2017.
- In 2018, the general SRA recruitment signals were down, compared to early survey years.
- HBB had quite low densities in 2002, 2005 and 2017–2018.
- No significant recruitment signals, except for YA in 1997.

For adjusted measures of spawning stock aged ≥ 1+ years in Table 9b, the surveys indicated:

- Densities varied across areas and years from one to 679 scallop per hectare. The median coefficient of variation per area-year estimate based on standard errors was about 17%.
- The low density of one scallop per hectare in SRA Yeppoon A in 2017 was alarming. Similarly, the estimate for Bustard Head at eight scallop per hectare. In general, the 2017 estimates were comparable to the low estimates in 1997, when the fishery was widely believed to be overfished.
- Only the K'gari and HBA areas had a sufficient density of 1+ aged scallops in 2017. Figure 26 spatially illustrates this. BHB was the only SRA that had a sufficient density of scallops in 1997.
- Surveys in 2000 and 2001 showed improved densities of scallops, generally for the SRAs after continual closure. Increased densities also occurred for BHA and HBA in 2004, YA in 2006, and BHA, BHB and HBA in 2018. The overall 2018 result was generally healthier than 2017, except for the K'gari area which was heavily fished through 2018 (Figure 26).

For 2018, density estimates of commercial sized scallops (Table 10) were used to guide potential fishery yields (Table 11). Potential recommended biological catches (RBC yields) for region 3 were about 164 t for F_{MSY} fishing and 110 t for more sustainable and profitable F_{B60} fishing (Table 11). These yields were from the calculation of commercial-legal-sized-density (≥ 9 cm) × area × 7.6 g meat weight per scallop (9 cm) × harvest-rate-proportion, scaled to tonnes (t). The RBC estimates were similar to the stock model estimates reported in Table 13. Estimates of RBC varied depending on the areas and the assumed survey catchability (Table 11).

Table 9. Mean modelled (kriging) scallop densities per hectare by survey area and year. Table (a) were 0+ aged densities for shell heights < 7.8 cm, and Table (b) for ≥ 1+ aged densities for shell heights ≥ 7.8 cm. Standard errors are in parenthesis. Symbol – indicates no survey. 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.

(a) 0+ densities, shell height less than 7.8 cm

Area name	Area (ha)	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2017	2018
Yeppoon	429753	46 (17)	19 (10)	4 (15)	40 (7)	-	-	-	-	-	-	32 (10)	13 (7)
YA	27711	447 (7)	38 (2)	83 (3)	134 (4)	160 (6)	176 (4)	69 (6)	87 (9)	129 (4)	42 (5)	230 (9)	51 (6)
YB	31680	26 (5)	81 (3)	10 (3)	84 (4)	18 (7)	79 (3)	38 (7)	39 (8)	87 (4)	15 (4)	47 (9)	50 (5)
Bustard Head	378213	81 (17)	17 (10)	16 (16)	22 (7)	-	-	-	-	-	-	16 (13)	22 (7)
BHA	31501	126 (7)	40 (3)	50 (4)	55 (4)	102 (13)	30 (3)	103 (5)	49 (11)	52 (3)	30 (3)	26 (8)	48 (6)
BHB	31516	142 (15)	62 (2)	34 (5)	32 (6)	64 (6)	35 (3)	79 (6)	60 (7)	22 (3)	19 (4)	17 (8)	62 (7)
Hervey Bay	264299	29 (15)	13 (6)	80 (13)	32 (7)	-	-	-	-	-	-	38 (11)	12 (7)
HBA	31401	68 (7)	24 (4)	286 (6)	144 (6)	15 (6)	17 (3)	62 (5)	116 (7)	28 (3)	12 (4)	20 (12)	36 (9)
HBB	30400	30 (8)	41 (2)	160 (3)	126 (4)	20 (6)	5 (3)	18 (5)	20 (7)	6 (3)	31 (4)	10 (7)	4 (6)
K'gari -Fraser Island	231445	-	-	-	-	-	-	-	-	-	-	9 (12)	58 (7)

(b) 1+ densities, shell height greater than or equal to 7.8 cm

Area name	Area (ha)	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2017	2018
Yeppoon	429753	42 (23)	49 (43)	36 (23)	91 (37)	-	-	-	-	-	-	50 (19)	117 (22)
YA	27711	16 (8)	101 (41)	109 (17)	423 (11)	452 (36)	22 (8)	92 (19)	31 (45)	98 (7)	346 (20)	1 (15)	177 (23)
YB	31680	63 (5)	60 (45)	104 (14)	144 (11)	464 (32)	23 (10)	72 (23)	41 (41)	133 (7)	217 (14)	122 (13)	181 (18)
Bustard Head	378213	58 (22)	81 (43)	114 (24)	59 (37)	-	-	-	-	-	-	8 (24)	127 (20)
BHA	31501	140 (7)	202 (42)	132 (15)	405 (11)	420 (54)	118 (8)	54 (23)	453 (56)	25 (6)	51 (13)	23 (11)	311 (22)
BHB	31516	650 (14)	271 (41)	234 (17)	316 (16)	357 (33)	177 (8)	157 (18)	162 (37)	53 (7)	160 (14)	33 (12)	373 (25)
Hervey Bay	264299	30 (14)	92 (43)	97 (21)	58 (37)	-	-	-	-	-	-	84 (18)	155 (25)
HBA	31401	109 (7)	181 (41)	258 (19)	305 (15)	244 (30)	94 (6)	63 (19)	678 (39)	138 (6)	176 (14)	271 (17)	328 (13)
HBB	30400	90 (9)	99 (42)	18 (17)	126 (13)	38 (29)	34 (6)	8 (18)	40 (39)	15 (5)	54 (14)	39 (10)	92 (21)
K'gari - Fraser Island	231445	-	-	-	-	-	-	-	-	-	-	592 (23)	15 (15)

Table 10. Mean modelled (kriging) commercial scallop densities per hectare by survey area and year. The densities were for commercial shell heights ≥ 8.8 cm. Standard errors are in parenthesis. Symbol – indicates no survey. 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.

Area name	Area (ha)	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2017	2018
Yeppoon	429753	32 (18)	41 (37)	28 (17)	70 (27)	-	-	-	-	-	-	26 (12)	66 (17)
YA	27711	11 (6)	79 (36)	93 (13)	224 (9)	167 (29)	14 (6)	36 (14)	13 (40)	61 (6)	121 (15)	0 (10)	159 (18)
YB	31680	48 (4)	39 (39)	77 (11)	107 (9)	442 (26)	14 (7)	59 (17)	22 (36)	117 (5)	135 (10)	64 (9)	137 (13)
Bustard Head	378213	46 (17)	60 (37)	83 (18)	42 (27)	-	-	-	-	-	-	6 (15)	50 (16)
BHA	31501	120 (6)	160 (36)	111 (12)	267 (9)	319 (42)	82 (5)	45 (17)	442 (50)	9 (4)	39 (9)	17 (8)	240 (18)
BHB	31516	536 (11)	181 (36)	164 (13)	169 (12)	227 (27)	103 (6)	121 (14)	123 (32)	39 (5)	140 (10)	25 (8)	164 (21)
Hervey Bay	264299	24 (11)	77 (37)	73 (16)	50 (27)	-	-	-	-	-	-	83 (12)	135 (20)
HBA	31401	80 (6)	175 (36)	231 (15)	280 (11)	240 (24)	91 (5)	56 (15)	653 (34)	112 (4)	135 (10)	255 (12)	318 (12)
HBB	30400	71 (7)	94 (37)	8 (13)	120 (10)	37 (24)	33 (5)	7 (14)	30 (34)	11 (4)	36 (10)	38 (7)	90 (16)
K'gari - Fraser Island	231445	-	-	-	-	-	-	-	-	-	-	447 (14)	11 (15)

Table 11. Yield reference points from the 2018 survey. The estimates were mean tonnages (scallop meat weight), with normal 95% confidence intervals in parenthesis. Harvest rates were from Table 13. Survey catchability assumed 0.6205. For a lower catchability of 0.3, potential yields will double in the table.

Reference point	Harvest rate fraction	All ten areas	Region 3	Region 3, no SRAs
F_{B40}	0.23	184 (166 : 203)	180 (164 : 196)	127 (114 : 141)
F_{MSY}	0.21	168 (151 : 185)	164 (150 : 179)	116 (104 : 129)
F_{B50}	0.19	152 (137 : 168)	149 (136 : 162)	105 (94 : 117)
F_{B60}	0.14	112 (101 : 123)	110 (100 : 119)	78 (69 : 86)

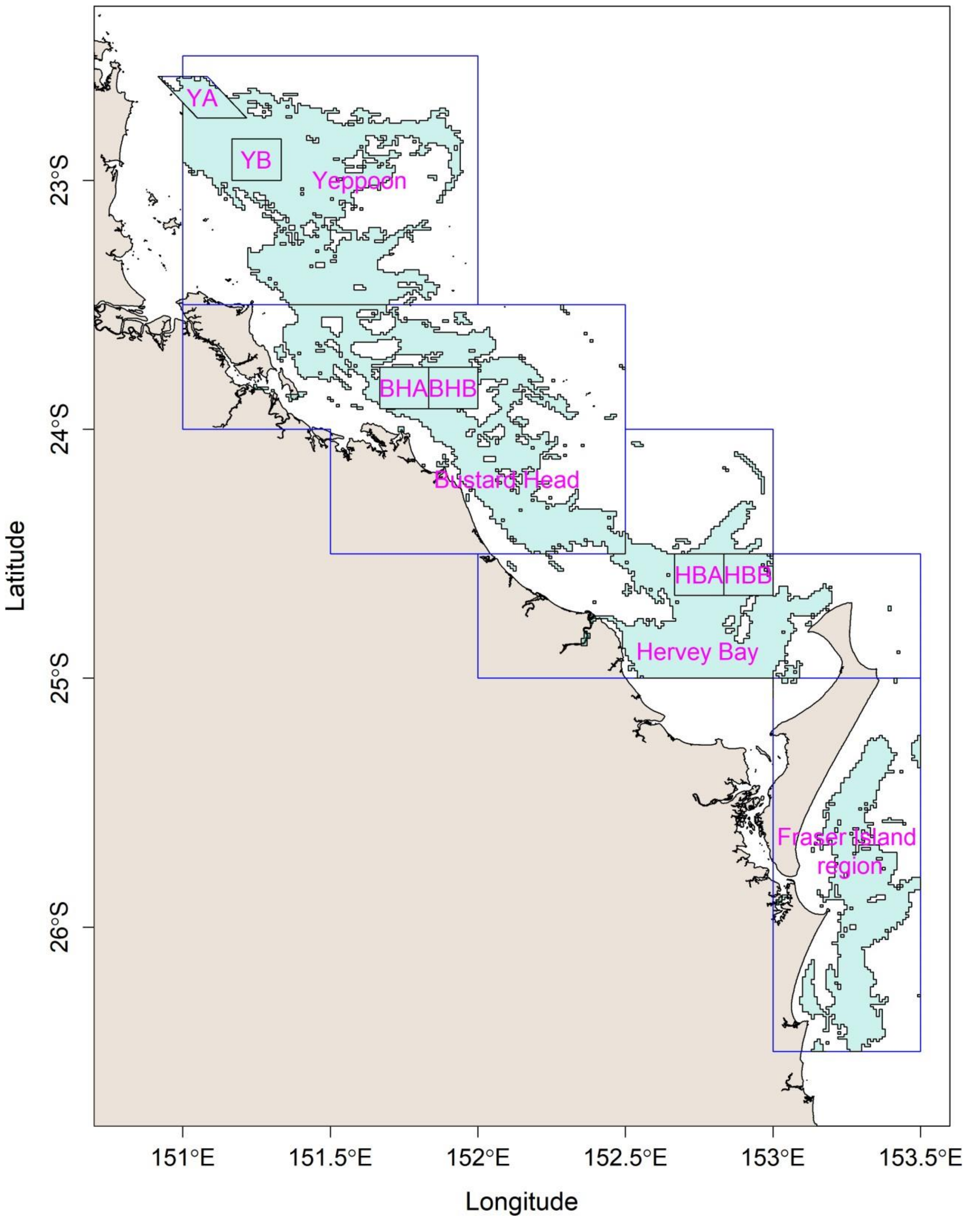

Figure 25. Illustration of the broader fished area (footprint) for scallop fishing, mapped from vessel VMS data having ≥ one hour of fishing. The area hectare measures are in Table 9. Scallop trawling was based on the vessel speed derived from VMS consecutive polling distances, and where the fishers reported a catch of scallop.

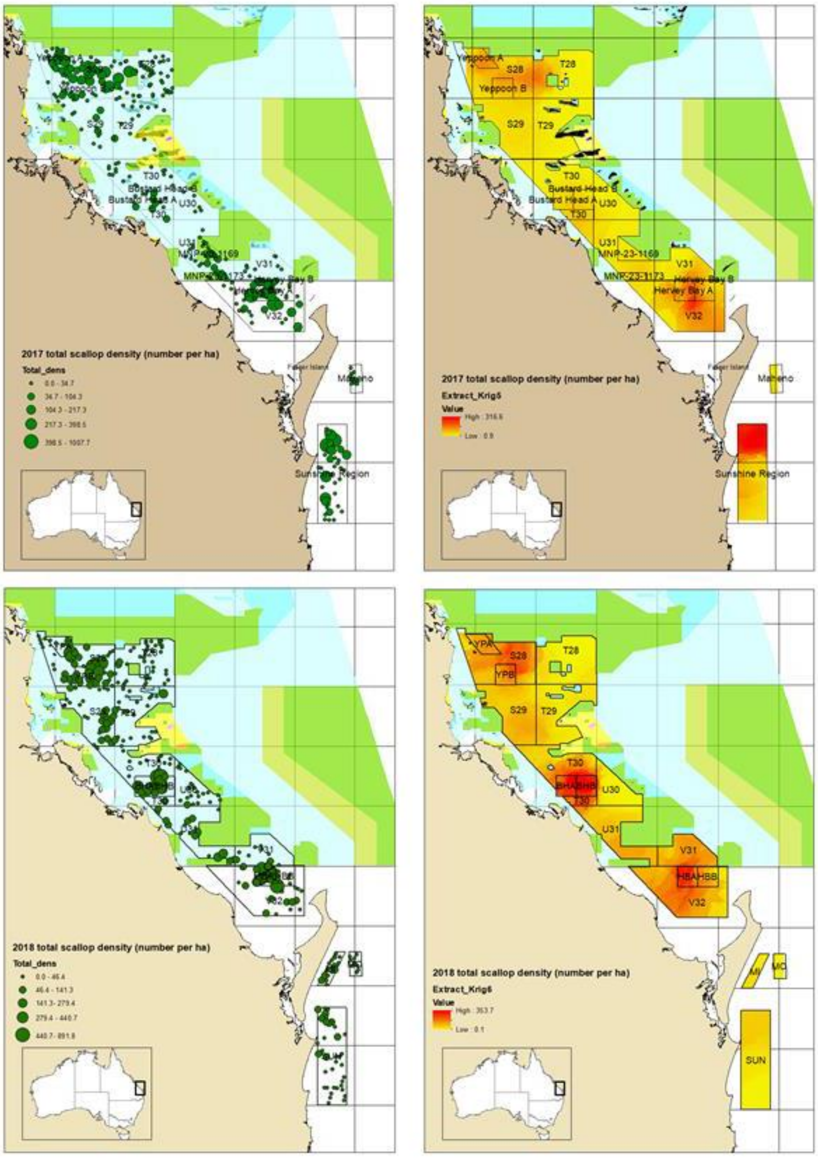

Figure 26. Observed (unadjusted) survey densities for all scallops 2017–2018. The left bubble plots illustrate the data and survey sites. The right plots illustrate the spatially modelled densities.

4.3.2 Model estimates

Biomass ratios were similar for the different survey catch efficiencies, and reported results mostly focussed on the midpoint 0.3 setting.

The models analysed natural mortality (*M*) with annual changes in mean winter SST. The logit form of linearly relating *M* and SST was greater for spatial-M1 modelling of 1977–2018 catch rates, than for 1988–2018 catch rates (Figure 27 and Figure 28). The log linear form, used in spatial-M2, estimated a more tempered relationship (Figure 29). The assumed survey catch efficiency did not change estimates. Results were sensitive to changing natural mortality with related SST effects.

Based on the data, estimates of temperature varying *M* in recent years 2016–2018 were above the mean in all analyses (Figure 27, Figure 28 and Figure 29). The modelled consequence was for conditions for reduced scallop survival, abundance and fishery yield. This result, in the context of future fishery management and harvest strategies, suggested harvest/effort control rules might need allowance for high *M*, in the order of 8% suggested by the range change in *M*. This is an important consideration, given that many years in the last two decades experienced above average winter SSTs, in the order of 0.5–1.0 °C warmer waters than the reference winter SST of 21.096 °C for 1977, when Dredge (1985) tagged scallops. (Figure 27).

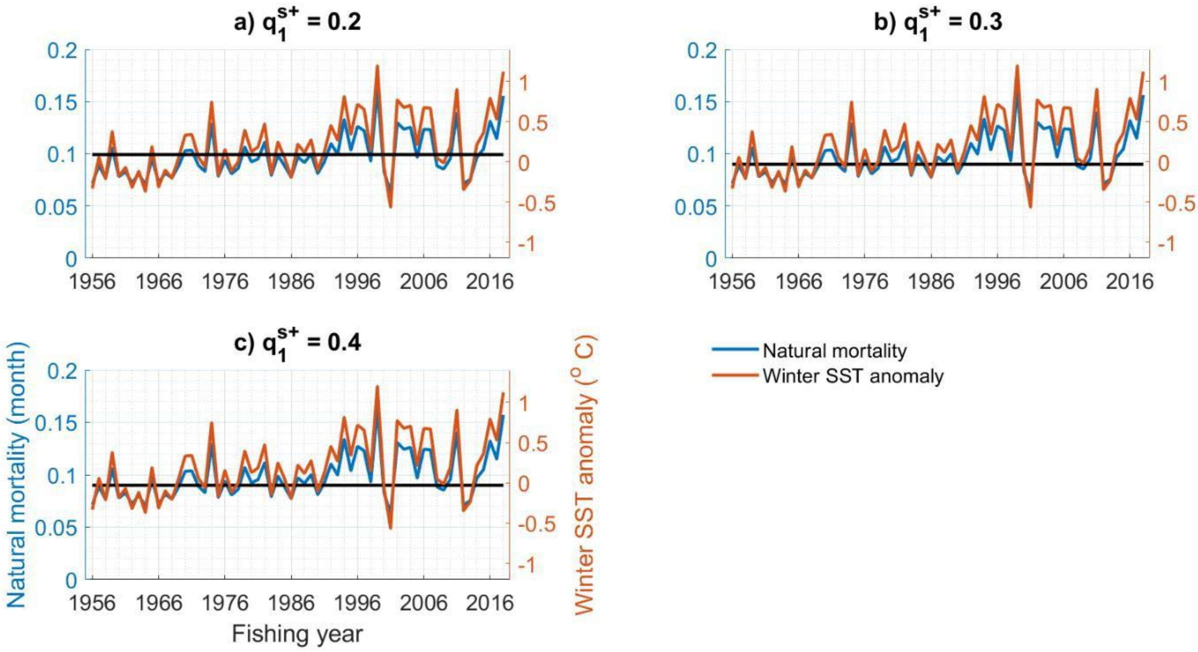

Figure 27. Natural mortality predicted from the spatial-M1 model using catch rates 1977–2018, for a) survey catchability 0.2, b) 0.3, and c) 0.4. Per cent scale = 1-exp(-M).

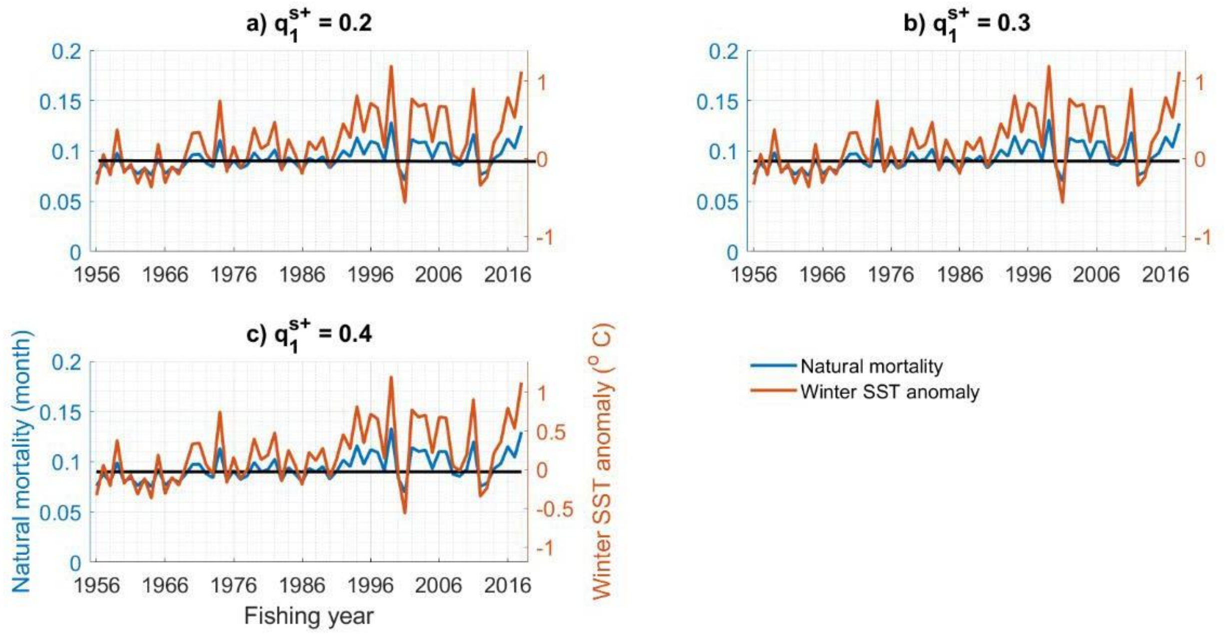

Figure 28. Natural mortality predicted from the spatial-M1 model using catch rates 1988–2018, for a) survey catchability 0.2, b) 0.3, and c) 0.4. Per cent scale = 1-exp(-M).

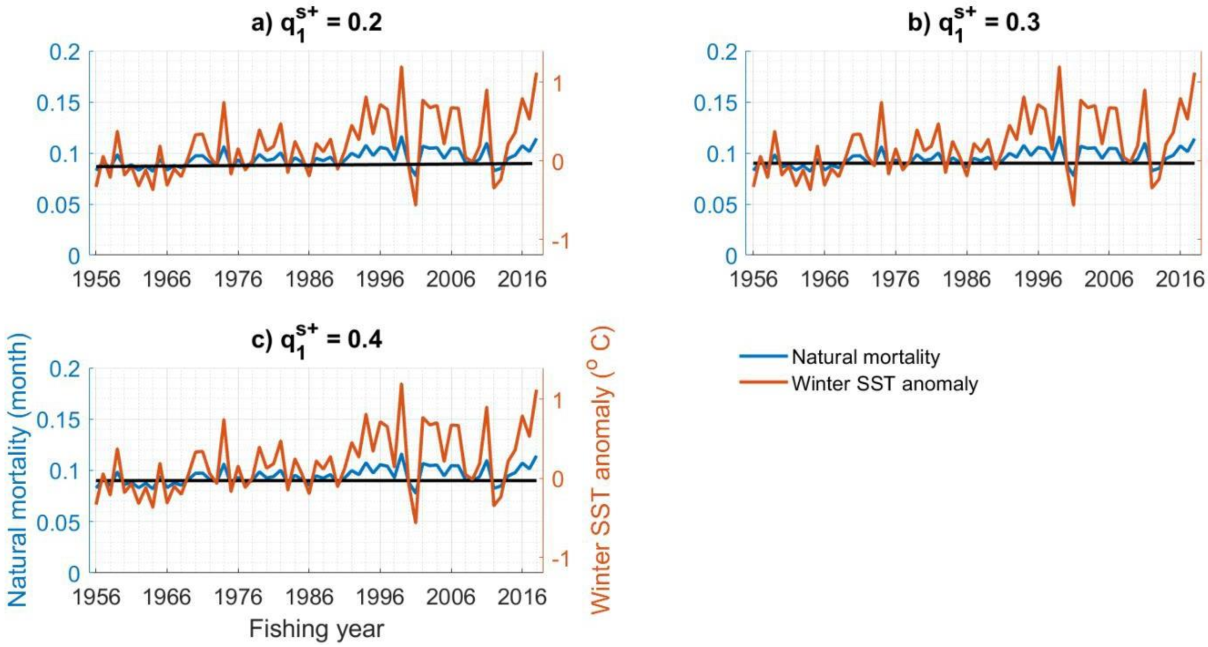

Figure 29. Natural mortality predicted from the spatial-M2 model using catch rates 1977–2018, for a) survey catchability 0.2, b) 0.3, and c) 0.4. Per cent scale = 1-exp(-M).

The resulting influence of temperature varying natural mortality (*M*) was significant on measures of spawning biomass. Trends in Figure 30 diverged between two versions of the ten-area spatial model. This was due to the higher temperature-M (logit) effects, lower estimated steepness at the 0.2 limit, differences in the negative log-likelihood functions, extra parameters and method used to control occurrences of high harvest rates approaching 100% to calibrate the spatial-M1 model (Table 6, on page 23). The spatial-M2 calibration also resulted in low steepness between 0.2 and 0.3, but gradually penalised overly high harvest rate solutions > 80%, to produce a higher prediction with more tempered recruitment deviations. Apart from these key differences in calibration, both models had the same population dynamics.

In Figure 30, spatial-M1 spawning biomass ratios diverged early. This related to higher monthly *M* from spikes in SSTs in 1959–60, 1965 and 1974. The spatial-M1 stronger temperature effect, high 1988–2018 recruitment deviations (log standard deviation = 0.68), and no recruitment compensation behaviour with steepness near 0.2, set the biomass trajectory on a lower path than the spatial-M2 model. From 1977, when catch rate information was available, the trend in the models were generally similar. The spatial-M2 trend, with marginal recruitment compensation around 0.26 and the deviations (1988–2018 log standard deviation = 0.44), predicted an increased 2008–2009 spawning biomass above 20%. The increase was in the catch rate data (Figure 18). Estimated spawning biomass ratios, with SST affecting *M*, were low in 2015–2018, around 10% of 1956 levels (Figure 30).

To expand on results in Figure 30, the separated mortality components illustrate the relative roles of SST and harvests on scallop survival (Figure 31). Figure 31 summarised annual mortality components, across areas, in the population equation for scallop survival, exp(-Z) (equation 5 in Table 28, on page 78 Appendix 12.4). In Figure 31, the relative SST effect measured change in natural mortality from the mean instantaneous rate of 0.09 per month, and compared against the relative harvest effect on scallop mortality. The model analyses and the resulting mortality fractions in Figure 31 suggested:

- The mortality effects were higher in the logit formulation in spatial-M1, than the log-linear form in spatial-M2. However, the patterns were the same.
- Before 1988 in Figure 31, the blue index for SST effect was proportionally higher than the harvest component (red index). This was when scallop biomass was higher.
- The blue index pre-1980 generally suggested better SST conditions for scallop spawning and survival (negative values below zero), except for the years of 1959, 1965, 1970, 1971, 1974, and 1979.

- Before 1980, the model analyses suggested the *M* and SST influences on scallop survival were more than the harvests (harvests shown in Figure 13, page 28).
- After 1988, the harvest effect increased to either match or dominate the mortality component (fraction).
- For example in 2001, the high harvest rate on available scallop negated the reduced scallop mortality from lower SST.
- The model results suggest that fishing has played a role in the depletion of scallops since the 1980s.
- Interestingly, the extreme flood years of 1974 and 2011 coincided with increased winter SST.

Figure 32 illustrated the influence of SSTs on the results of the models. Removing the SST–*M* relationship in spatial-M1 resulted in higher spawning biomass ratios. For the solution without SST, there was higher recruitment compensation and lower measures of harvest rates. The no-SST results, using 1977–2018 catch rates, suggested that catch rates fell sharply at about 12% spawning biomass in 2016 (Figure 32a). The estimate increased to 30% spawning biomass in 2018. Similar to findings from the Campbell model (described in 4.3.2.1), the result from using 1988–2018 catch rates and no temperature data was too varied and unstable (Figure 32b).

The result from the non-spatial model analysis suggested the 2018 region 3 spawning biomass was at 22% (95% confidence interval 17–32%) of virgin level in 1956 (Figure 33). The close-fitting confidence intervals were a product of the long-term decline in catch rates, steepness being low near its theoretical limit of 0.2 and –LL constraints. Broader uncertainty was revealed by comparing between model analyses, having different structural setups and assumptions. These results, considering 95% confidence intervals around predictions were generally ± 5–10% on all biomass ratios, suggested the 2018 region 3 spawning biomass was below 30–40% of virgin levels in 1956 (Figure 34).

Some example parameter estimates and model diagnostics are in the report Appendix 12.6, Figure 61 on page 97. As noted above, measures of reproductive rate *r* (or steepness *h*) were low. This important parameter indicates that the fishery needs to ensure that sufficient spawning biomass is present each year during winter to support future yields and profitability.

Annual recruitment variability (log standard deviation) was high between 0.44–0.54, scallop catchability/availability increased by 50–100% to match January catch rates when closures opened to fishing (e.g. the January effect is illustrated below in Figure 38 for catch rate reference points 2001–2016), and seasonal recruitment and catchability patterns were present.

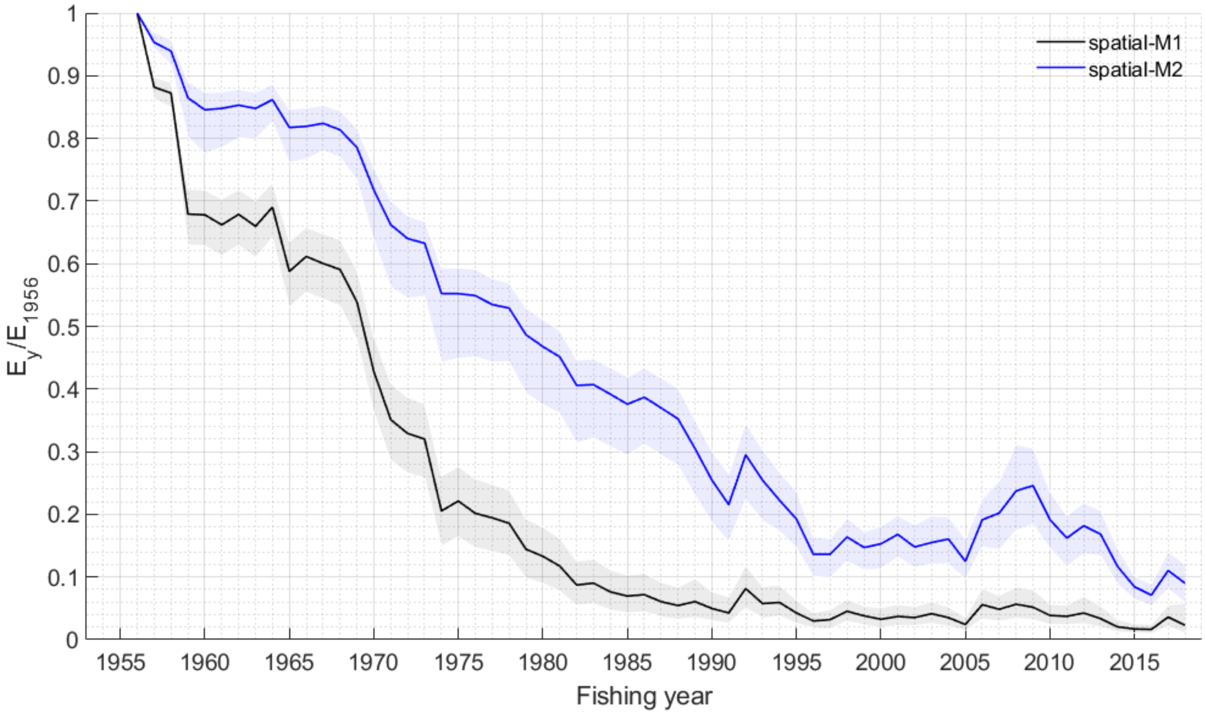

Figure 30. Spawning biomass ratios for increasing SST effects on scallop survival. The results were from the ten-area spatial models, using 1977–2018 catch rates, and survey 1+ catchability of 0.3. The differences between models are in Table 6, on page 23. The line-shades illustrate 95% confidence intervals from the MCMCs.

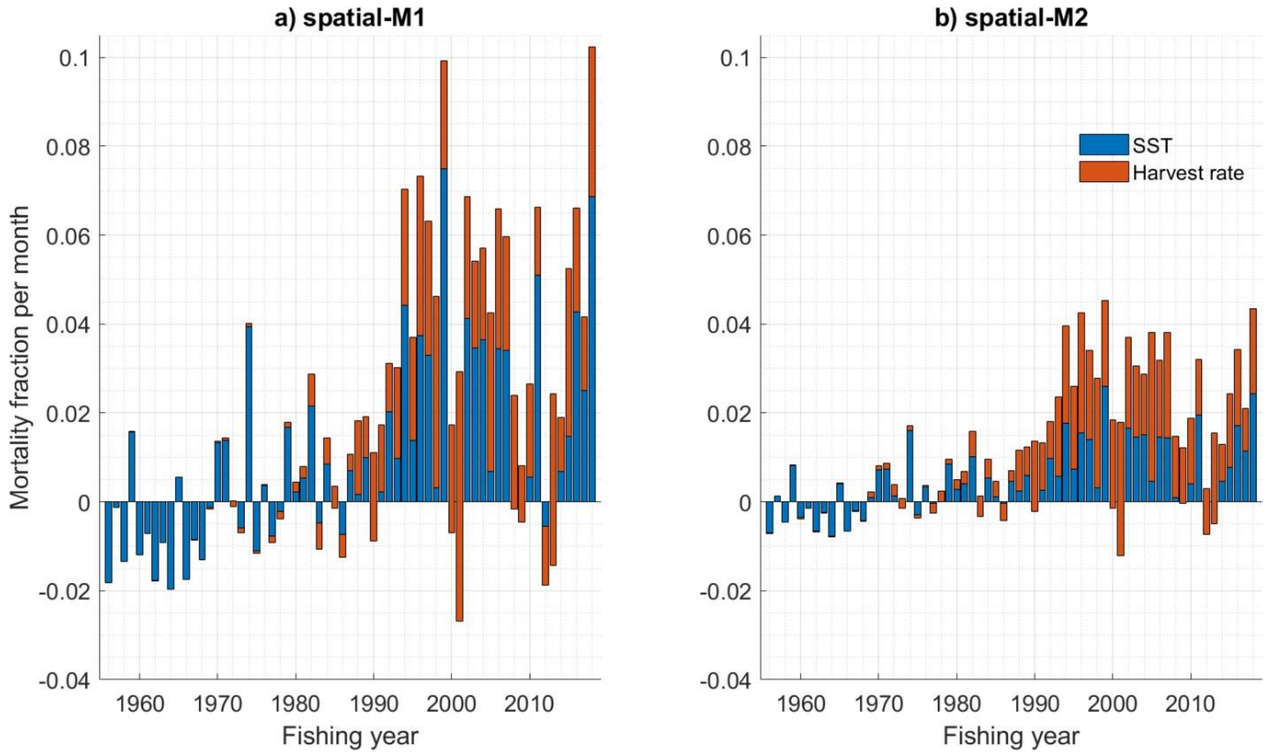

Figure 31. Relative mortality components, excluding the mean natural mortality of 0.09 per month, influencing scallop survival. The fractions were from the spatial-temperature models in Figure 30, and summarised annually. The figure first plots the winter SST component effect on M in blue, which can have a positive effect on M (i.e. below zero) or negative effect (i.e. above zero). Second, the harvest component increasing mortality was overlayed in red.

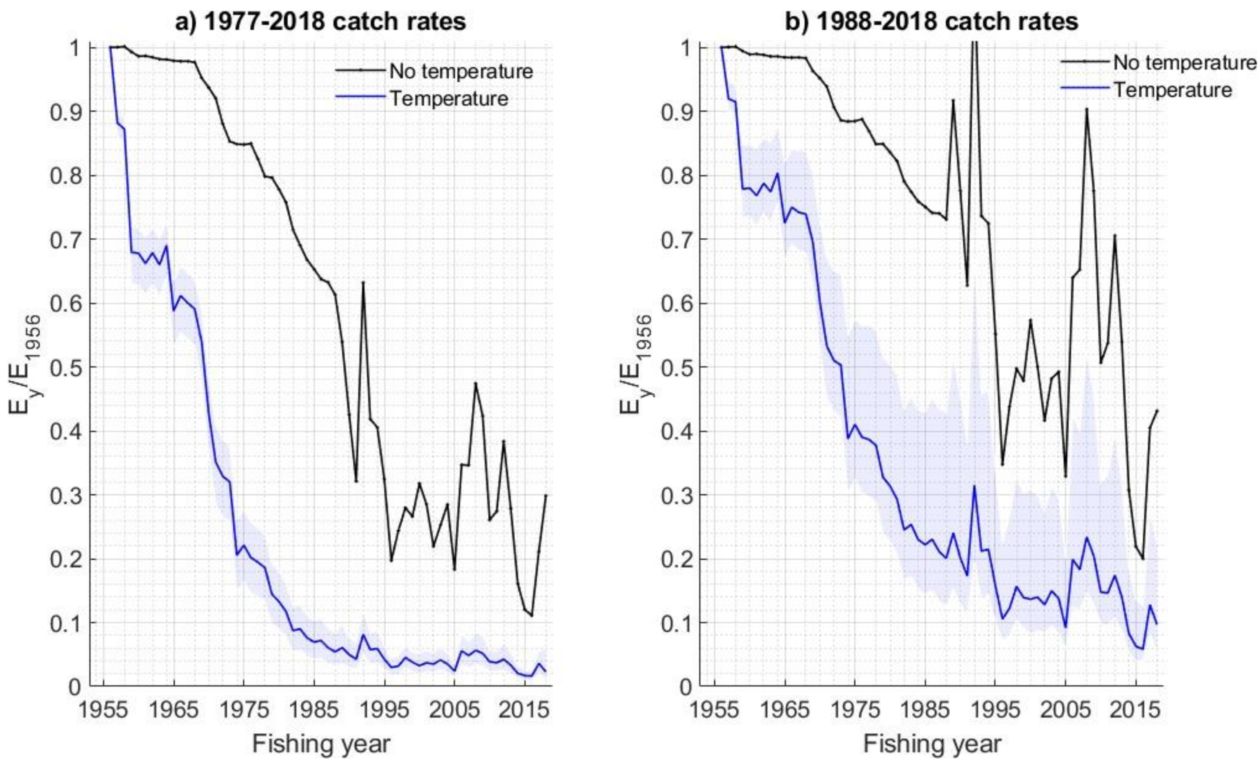

Figure 32. Spawning biomass ratios comparing results with and without increasing SST effects on scallop survival, for using a) 1977–2018 catch rates, and b) 1988–2018 catch rates. The results were from the spatial-M1 ten-area spatial model, using a survey 1+ catchability of 0.3. The line-shades illustrate 95% confidence intervals from the MCMCs.

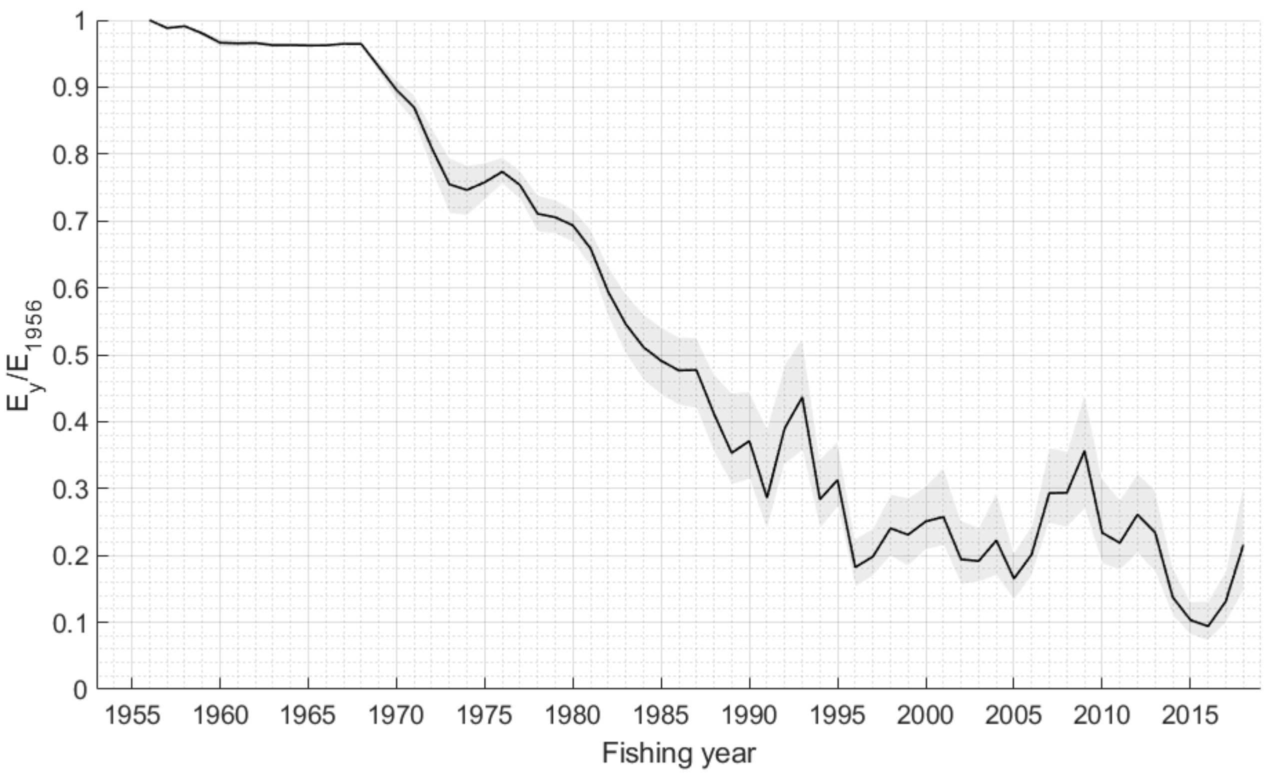

Figure 33. Spawning biomass ratio from the non-spatial model, using 1977–2018 catch rates, and survey 1+ catchability of 0.3. The line-shades illustrate 95% confidence intervals from the MCMCs.

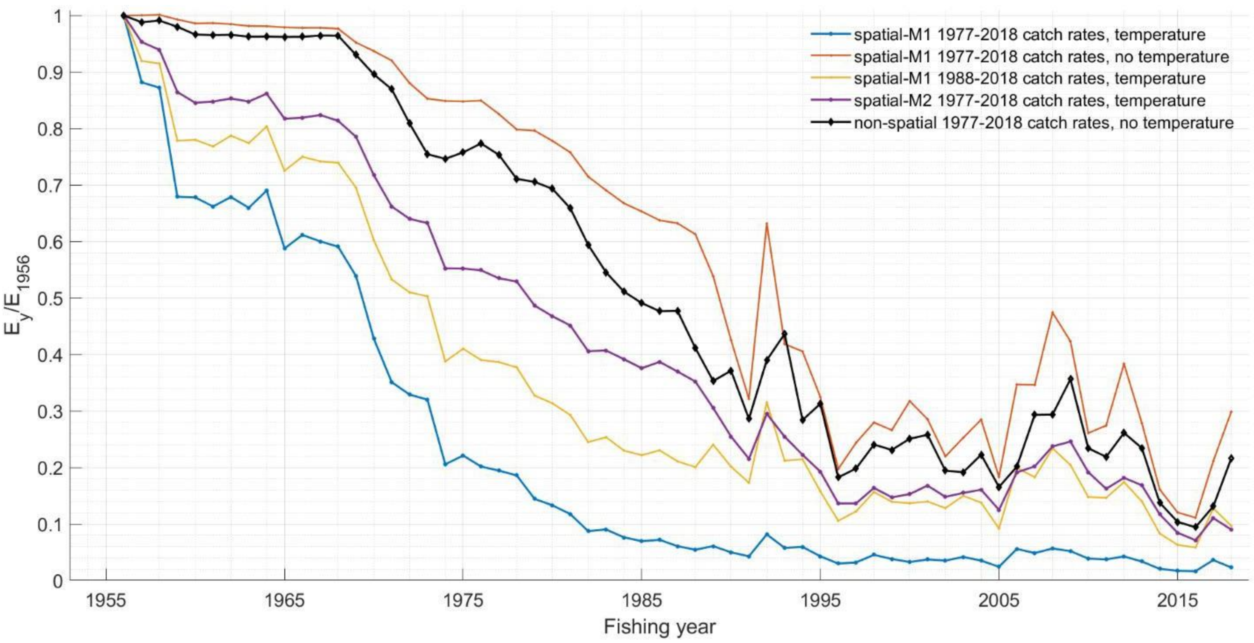

Figure 34. Spawning biomass ratios from select models, to demonstrate the range of predictions. All used a survey 1+ catchability of 0.3.

4.3.2.1 The previous model, Campbell et al. (2012)

Figure 35 showed the M1 spawning ratios from fishing years 1978-2018 related to fishing year 1977. The model predicted a low spawning biomass in 2016, with a marginal increase in 2017–2018. The 2018 spawning prediction was about 10% of virgin.

The estimated spawning ratios for M3 were very different to model predictions using the 1977-2018 catch rates (Figure 35). The Campbell model estimated higher and more variable spawning biomass ratios without the knowledge from the pre-1988 catch rates. Sensitivity analysis revealed that Campbell's model was unstable for M3 using 1988–2018 catch rates (Figure 36). The 2016 stock assessment reported that the result of M3 was less reliable with large confidence intervals (Yang et al., 2016). Hence, M3 was not an acceptable result.

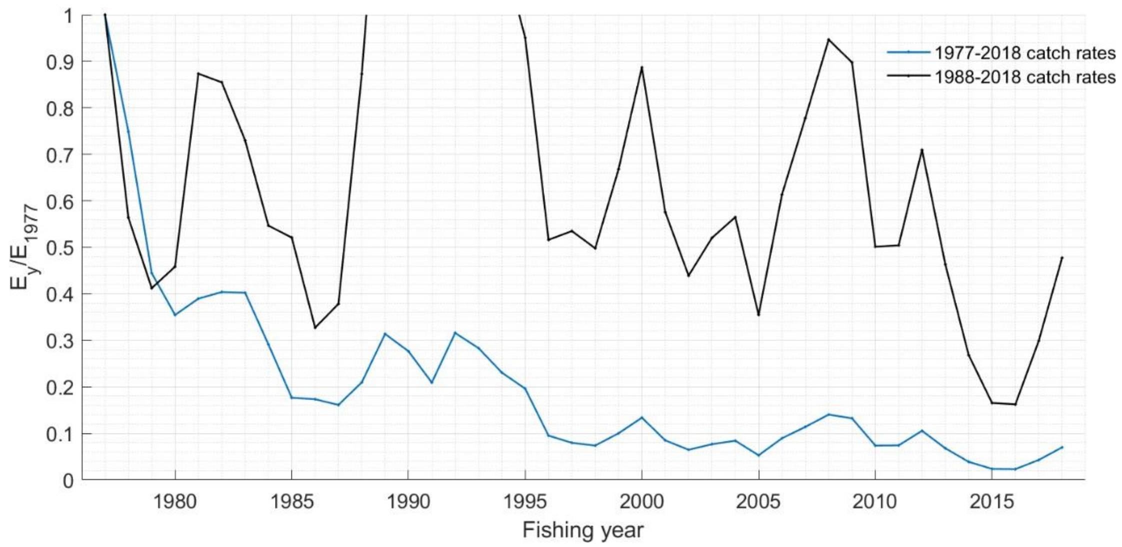

Figure 35. Spawning biomass ratios from the Campbell et al model.

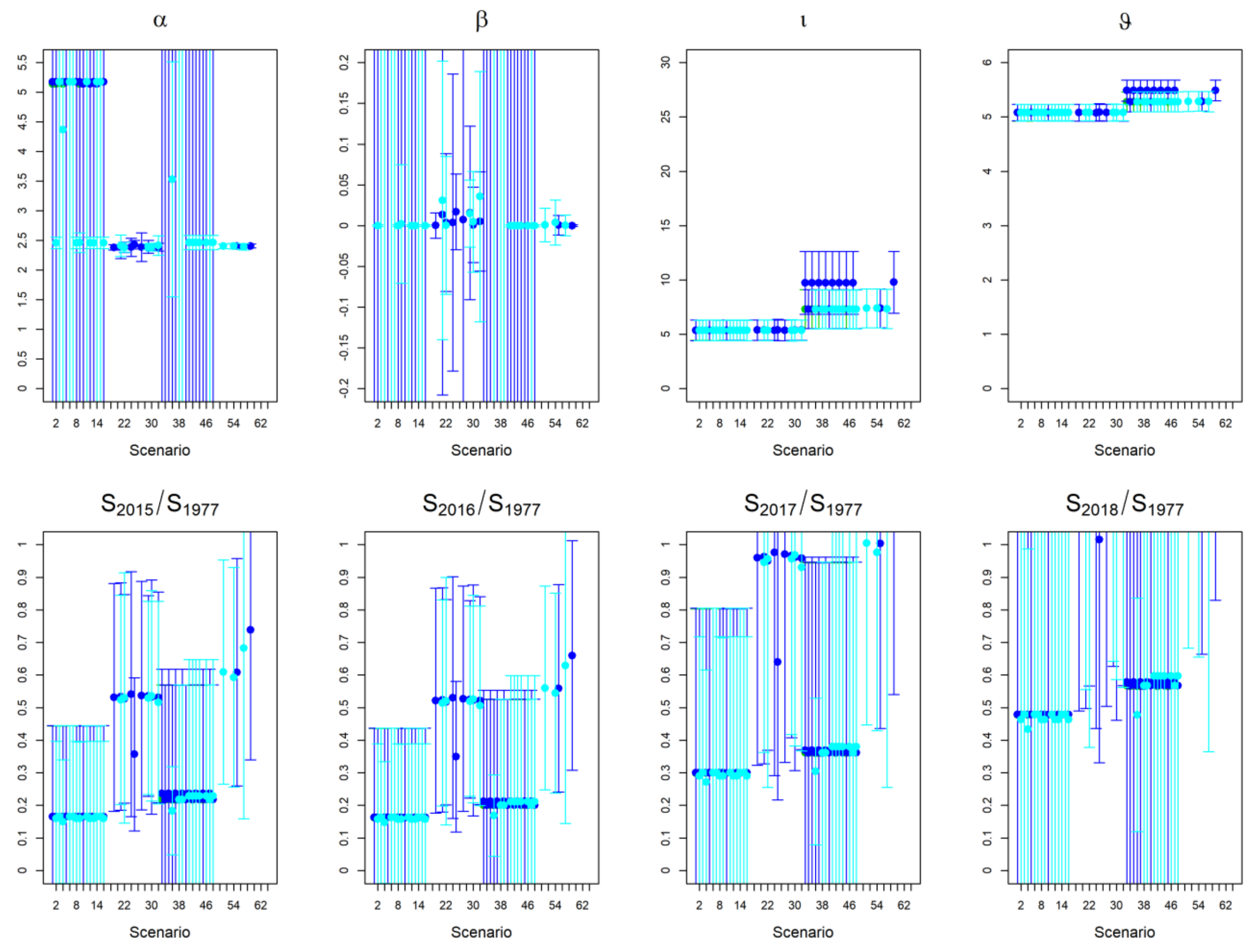

Figure 36. Sensitivity analysis of Campbell's model for scenario 2 (1988–2018 catch rates) showed that the results from M3 were not stable. Scenarios represent different optimisations. The S ratio labels are the same as the spawning ratio E labels in other figures.

4.3.3 Indicators and reference points

The development and reporting of fishery status indicators are crucial for the provision of information needed to manage fished stocks. It is equally vital for underpinning management procedures that seek to reach stock sustainability goals (Sloan et al., 2014).

Fisheries Queensland is planning new management procedures for the scallop fishery. Appropriately, this report provides new information on scallop indicators and reference points to support procedures for region 3 (Figure 3).

In summary, region 3 indicators and reference points (for spawning biomass, fishing harvest, effort and catch rates) assumed a constant rate of natural mortality (*M*) in time. However, reference points were less clear, complex, and impractical in the planned management procedure when results were split spatially or when *M* varied in time with changing SST. Simple biomass projection methodology (Richards et al., 1998), based on levels of fishing effort rather than specific reference points, were easier to investigate than spatial and temperature-dependent estimates of *M*. Results provide options to avoid over-harvesting, and help promote more profitable and successful fishing.

The non-spatial model (region 3) generated the equilibrium reference points (Table 12) and calculated that:

- The maximum sustainable yield was around 430 t. This was at a B_{MSY} of 45% of unfished 1956 biomass. This equilibrium point was associated with a standardised effort of 2243 boat-days per year. Boat-days were standardised according to a modern day vessel. That is a vessel with 337 HP, fishing 12 hours a night, with sonar, GPS, quad gear and drop chain (Table 26). This was for a boat of around 55 standardised hull units. Effort units = standardised days × standardised hull units (O'Neill and Leigh, 2006).

- Estimated equilibrium yield at B_{60} was 393 t, with associated effort of 1521 boat-days per year.
- Estimated equilibrium yield at B_{50} was 425 t, with associated effort of 1977 boat-days per year.
- Estimated equilibrium yield at B_{40} was 427 t, with associated effort of 2475 boat-days per year.

A plot of the total harvest from region 3 (Yeppoon, Bustard Head and Hervey Bay) showed that since 2013 harvest was below MSY and equilibrium yield for B_{60} (Figure 37). Furthermore, estimated spawning biomass ratios in 2018 were less than levels of B_{MSY} or B_{60}. Higher biomass is required to attain potential equilibrium harvests.

A plot of observed catch rates and equilibrium catch rates in Figure 38 showed that since 2015 observed catch rates have always been below all three equilibrium catch rates.

Table 13 shows the expected yields, for harvest rates applied to the 2018 biomass. For fishing 2018 biomass at MSY, the yield is around 161 t, which was about the current 2018 harvest in region 3. The effort to fish the 161 t would correspond to the same number of boat-days at equilibrium MSY. Thus in order to rebuild the scallop population to a higher level, the fishing effort may need to be less than current.

Table 12. Equilibrium reference points for region 3. F represents the equilibrium harvest rate, listed in Table 13. The estimates were medians from MCMC, with 95% confidence intervals in parenthesis. The estimates assumed the 2017–2018 pattern of fishing, with SRAs closed.

Equilibrium	Yield (tonnes)	Effort (boat-days per year)	Effort units	Catch rate (baskets per boat-day)
F_{B40} at B_{40}	427 (360 : 497)	2475 (2151 : 2863)	136101 (118318 : 157447)	23 (21 : 25)
F_{MSY} at B_{MSY}	430 (363 : 499)	2243 (1938 : 2642)	123338 (106613 : 145291)	25 (23 : 28)
F_{B50} at B_{50}	425 (360 : 490)	1977 (1723 : 2271)	108729 (94744 : 124893)	28 (26 : 32)
F_{B60} at B_{60}	393 (333 : 448)	1521 (1330 : 1739)	83661 (73158 : 95625)	34 (31 : 38)

Table 13. Reference points for 2018 region 3. The estimates were medians from MCMC, with 95% confidence intervals in parenthesis. The estimates assumed the 2017–2018 pattern of fishing, with SRAs closed.

Current	Harvest rate fraction	Yield (tonnes)	Effort (boat-days per year)	Effort units
F_{B40} at B_{2018}	0.23 (0.16 : 0.33)	177 (140 : 229)	2466 (2150 : 2836)	135656 (118244 : 155971)
F_{MSY} at B_{2018}	0.21 (0.15 : 0.31)	161 (127 : 211)	2239 (1940 : 2623)	123128 (106675 : 144265)
F_{B50} at B_{2018}	0.19 (0.13 : 0.26)	142 (113 : 183)	1979 (1728 : 2266)	108861 (95064 : 124614)
F_{B60} at B_{2018}	0.14 (0.10 : 0.20)	110 (87 : 141)	1530 (1341 : 1744)	84175 (73741 : 95943)

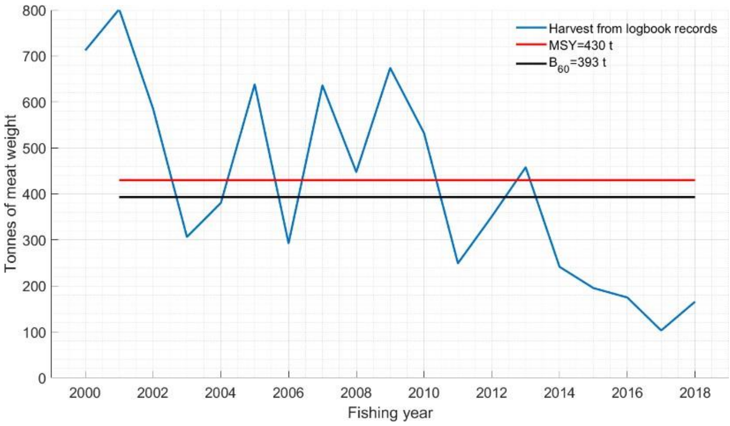

Figure 37. Harvest records for region 3 (Yeppoon, Bustard Head and Hervey Bay, and excluded K'gari).

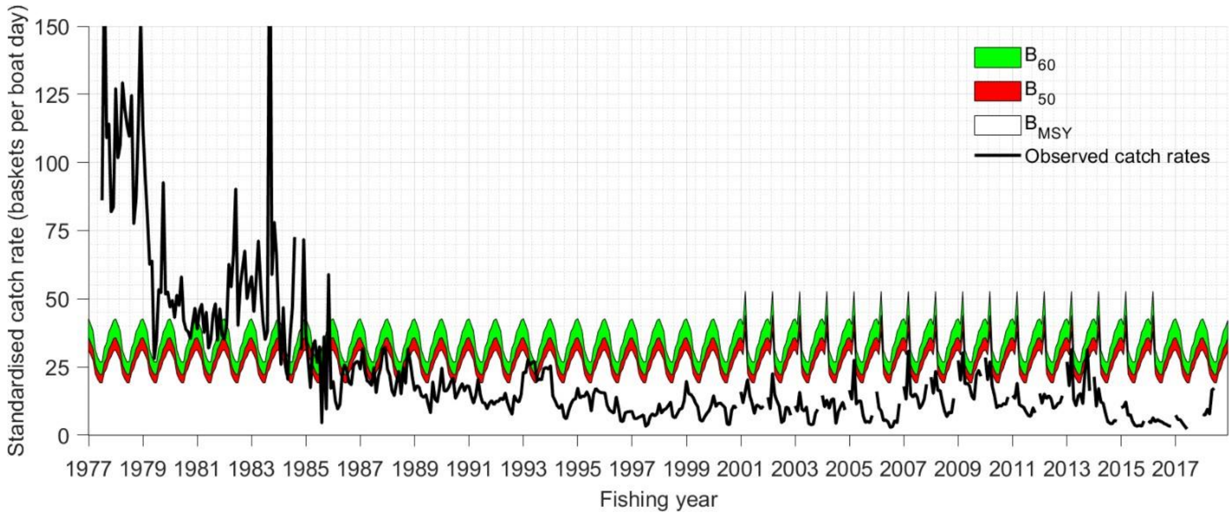

Figure 38. Standardised catch rates and reference points for region 3 (Yeppoon, Bustard Head and Hervey Bay). The white area represents biomasses less than B_{MSY}, the red area between B_{MSY} and B_{50}, and the green area between B_{50} and B_{60}. The reference points were for a commercial 9 cm minimum legal size.

The non-spatial forward projections of fishing effort (Table 7, page 25) are in Figure 39. Under no fishing, the spawning stock biomass ratio (labelled E) increased to almost virgin state after 20 years. Under MSY fishing effort and current fishing effort pattern (i.e. six-month fishery), the spawning stock approached 43% after 20 years, which was near the 45% ratio under MSY equilibrium. For the fishing efforts projected, except for 5000 boat-day example, the spawning stock generally increased after 20 years, with the six-month fishery having slightly higher spawning ratios than the four-month fishery. Under a high fishing effort of 275 000 effort units (or 5000 boat-days), the spawning stock declined.

For a proposed status quo fishing effort of 118 000 units, the spawning stock after 20 years reached 43% and 39% for the six-month and four-month fisheries respectively. The four-month fishery projection had lower ratios than the six-month, due to the same effort fished at high concentration. The stock benefits of a four-month fishery would be realised with a proportional matching of reduced effort.

For the four-month fishery, harvest reached levels of 395 t after 20 years (Figure 39). A six-month fishery reached marginally high harvest levels of 406 t after 20 years.

Average annual catch rates for the four-month fishery reached about 22 baskets per boat-day after 20 years, and about 24 baskets per boat-day for the six-month fishery (Figure 39).

Figure 40 shows the number of years required to attain the reference points, for a range of fishing efforts. For example, spawning levels were around 40% (E_{40}) after 16 years, for a six-month fishery and 118 000 effort units.

The horizontal dotted line in Figure 40 was based on a recovery time that was suggested by the Australian Government (Australian Government, 2007). For saucer scallop, the calculation was as follows: recovery time is the minimum of 1) the mean generation time plus ten years, or 2) three times the mean generation time (Australian Government, 2007). The mean generation time is the average age of a reproductively mature animal in an unexploited population. For saucer scallops, the mean generation time is about 1.5 years. Thus based on the Australian Government (2007) definition, a suggested recovery time for the saucer scallop population could be three times the mean generation time, namely five years. Note that no recovery time lines currently exist in Queensland Government policy.

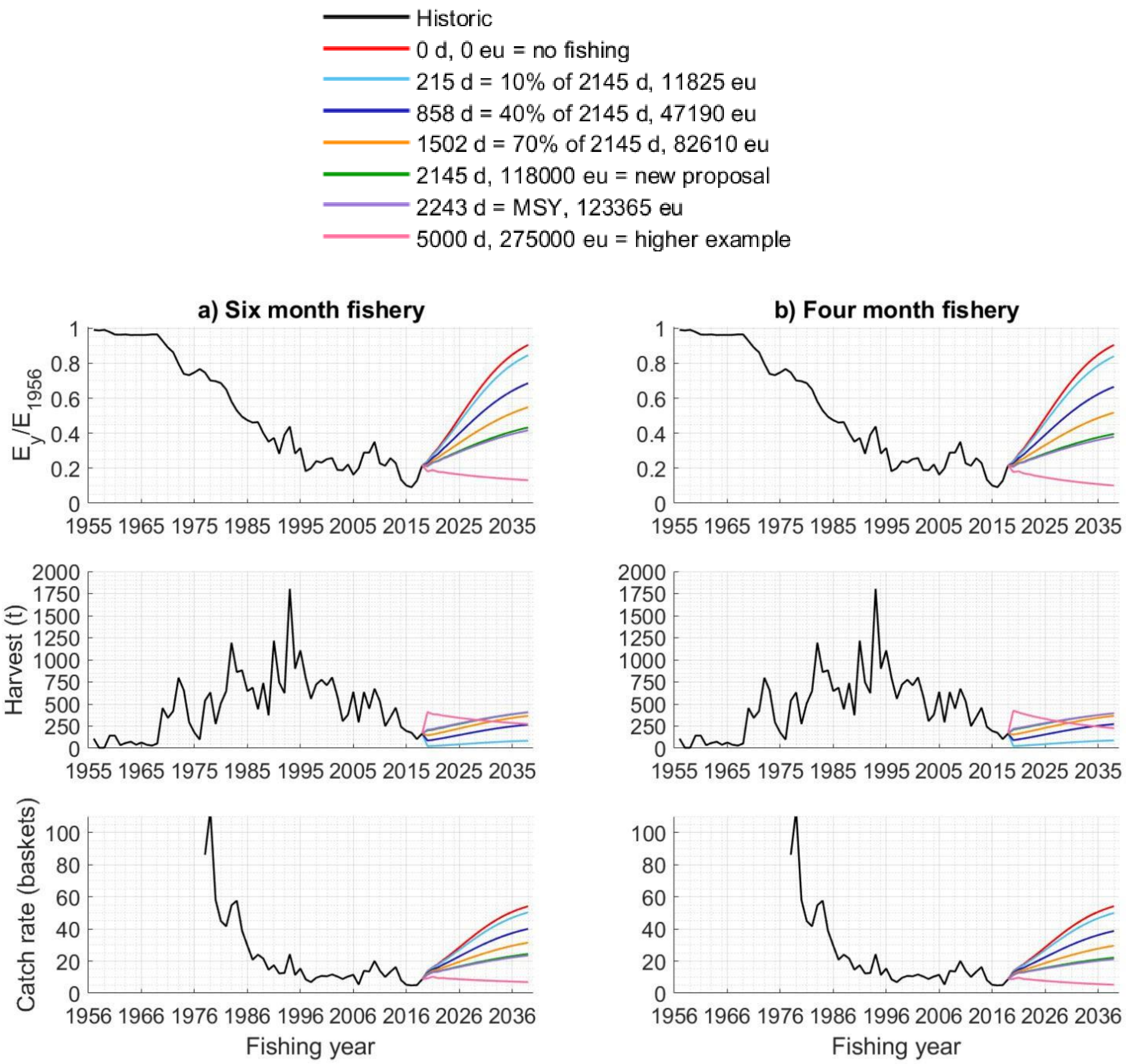

Figure 39. Simple forward projections of a range of annual fishing efforts, for a) depositing the effort into a six-month fishery, and b) into a four-month fishery. Each row of plots illustrate forecasts for the annual spawning biomass ratio, harvest and catch rate. The projections assumed deterministic recruitment in the non-spatial model for region 3.

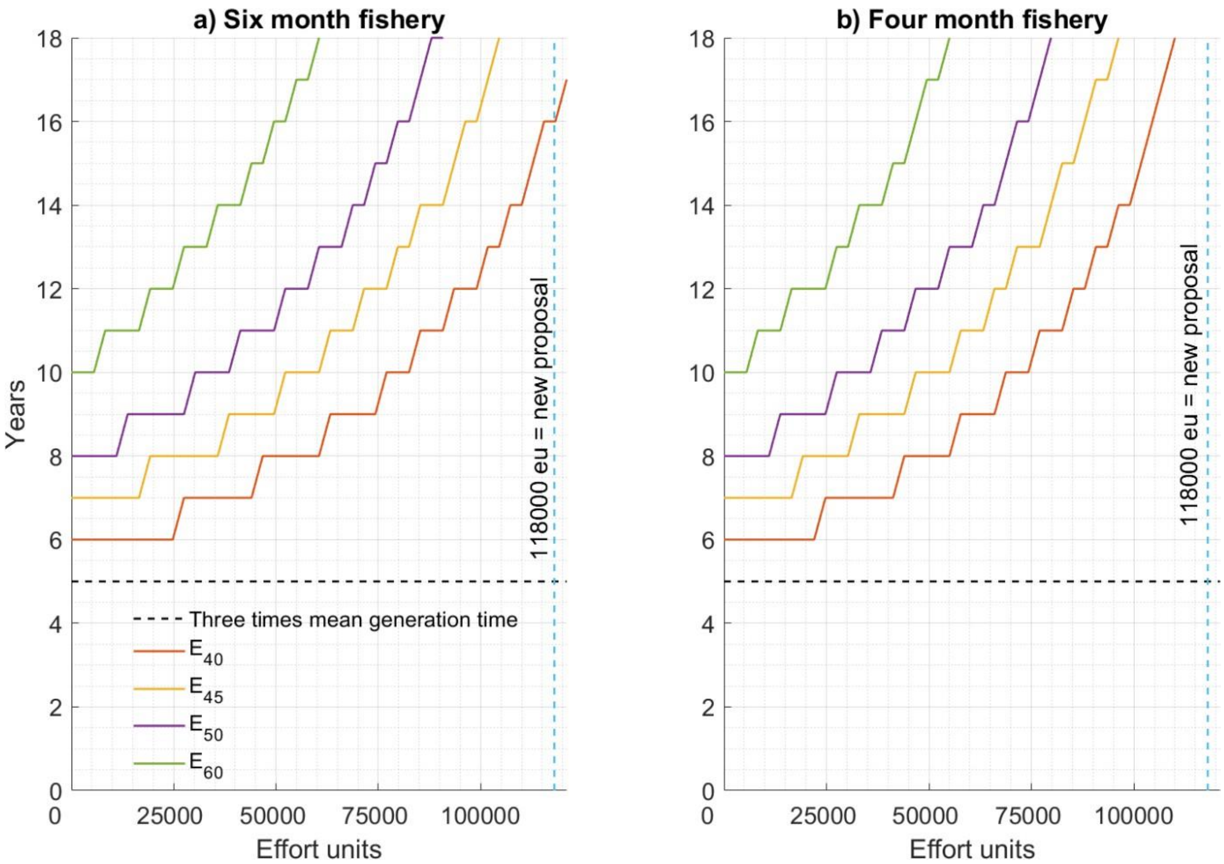

Figure 40. Projected recovery times (years on y-axis) for a range of annual fishing efforts (effort units on x-axis) to achieve spawning biomass reference points (E), for a) depositing the effort into a six-month fishery, and b) into a four-month fishery. The projections assumed deterministic recruitment in the non-spatial model for region 3. The new proposal line was a hypothetical value discussed in early management meetings with industry.

The projections that used spatial models with SST-influenced natural mortality were more speculative, more complex, and required subtle understanding (Figure 41). The outline of projection settings for spatial-M2 is below Table 7, page 25.

Under the SST scenario for 1900–1950, spawning biomass reached 34% of E_0 after 20 years, if there was no fishing pressure in future years (Figure 41a). Under a proposed fishing effort of 118 000 effort units (eu), spawning biomass was 30% of E_0 after 20 years, under the assumption that future SSTs were around those observed from 1900–1950. Under higher fishing pressure of 275 000 eu, spawning biomass increased to only 26% after 20 years for the past SST scenario.

If SSTs were projected to be the same as the 1999–2018 period, then spawning stock did not recover, irrespective of the fishing effort or recruitment deviation (Figure 41b). Spawning biomass was 5% after 20 years even under no future fishing pressure.

From the depleted spawning stock in 2018, which was near 10%, Figure 41 projections illustrated that recruitment deviations and SSTs might limit population growth. Generally, there was little difference in future spawning ratios between the projected fishing efforts less than 5000 boat-days. Results in Figure 41a mimicked improved habitat and environmental conditions for scallop survival, via reducing average SSTs. Whereas, if SSTs remained similar to those during 1999 to 2018 (above average), then population growth may be more limited.

All projection results were illustrative, to help inform fishery management decisions. It was impossible to speculate future outcomes, SSTs, recruitment deviations, and zone-by-month harvest rates. Although they were speculative, the dramatic difference between forecasts in Figure 41a, and Figure 41b were evidence to treat rising SST effects seriously.

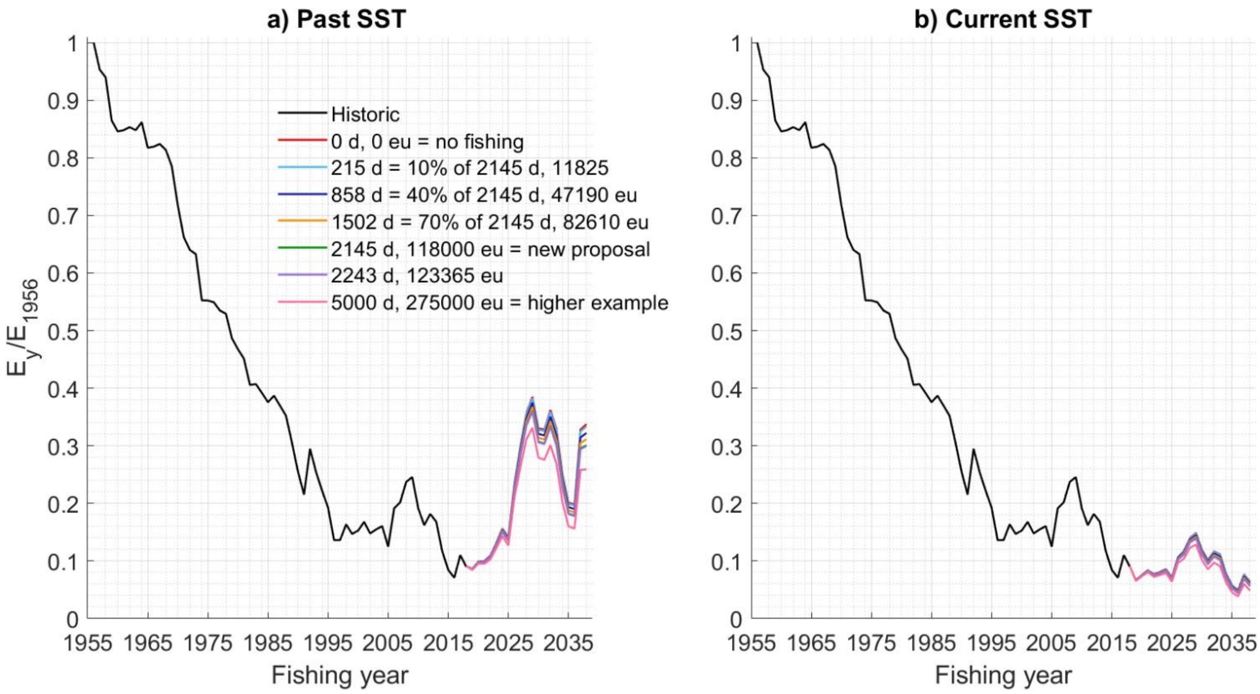

Figure 41. Spawning stock ratios (E) for various levels of fishing effort and two levels of sea surface temperatures a) constant equal to the 1900–1950 average, and b) equal to the 1999–2018 annual pattern. Projected recruitment deviations used the 1999–2018 pattern, for spatial-M2.

5 Discussion

The scale of increase in SST over years was not immense, but the increasing trend was clear from the data. For Western Australian saucer scallops, which experienced a sudden marine heat wave event in the summer of 2010/11, the SST anomalies were in the order of 2–4 °C above average (Caputi et al., 2014); much higher than for Queensland scallop between 0.5–1.0 °C (Figure 27). Irrespective of the scale, increasing SSTs may affect population levels of scallops, and may have lasting effect of reduced survival or recruitment of scallops. The occurrence of SSTs conducive for spawning is crucial to ensure adequate recruitment, larval development and scallop survival (Caputi et al., 2014).

Interestingly, based on SST data, it has been hypothesised that SST affects other winter-spawning species. For example, it was hypothesised that the length of spawning seasons for long-lived snapper in Queensland was reduced when SST forecast data were increased (P Hamer work for: Wortmann et al., 2019). For Queensland scallops, the monitoring of SST patterns may help understand the annual variation in the timing and length of spawning season, which could inform harvest strategy decision making.

While scientifically interesting, the results from using SST were difficult to interpret for the purpose of fishery management, and the models could not calculate usable reference points. This was because of the changing values of *M*, and the associated impact on the spawner-recruitment dynamics. Use of such an approach in fishery management would introduce unwanted complexity.

In addition, the performance of the spatial models was limited by assuming common recruitment deviations across zones. This was to avoid compounding the number of estimated parameters for the full recruitment variation (interaction) between years and zones.

All analyses resulted in model convergence (maximum likelihood estimates), and satisfactory goodness of fit to the trends in data. However, the structures and settings of the model could not predict all catch rates or densities perfectly. This indicates some variance in the data remains unexplained, and the random temporal-spatial patterns of residuals were difficult to separate between errors relating to data observations, scallop catchability and abundance dynamics of scallop recruitment and survival. Testing of –LL constraints helped improved sensible estimates, but did limit MCMC behaviour. All models responded poorly to high steepness, and it was a challenge to estimate away from the theoretical (linear) low limit of 0.2. Therefore, estimates of steepness and virgin recruitment R_0 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).

The primary assumption in the modelling was that the Queensland voluntarily recorded pre-1989 catch rates were standardised suitably against post-1988 catch rates. The pre-1989 catch rates provided crucial contrast to model change in abundance between 1956 and 2018. Without this contrast, model outputs were less certain as found for analyses using only 1988–2018 catch rates. To standardise pre-1989 catch rates to the 2018 fleet, fishing power characteristics were set to be the same as those of the 1970–1980 vessels. Further work is required to verify historical pre-1989 standardised catch rates and fishing power.

6 Conclusion

This project has described data, methods, analyses, and results to inform management procedures, and to explain the respective roles of fishing and environmental influences on saucer scallops. It has also highlighted new models for setting sustainable harvest and fishing effort. In this regard, the results demonstrated the importance of using and regularly conducting surveys to help calibrate information for fishery stock assessment and management. This has produced results to help understand and rebuild the scallop fishery. The work contained in this report has national relevance to other scallop fisheries.

6.1 Associations between saucer scallops and environmental variables

Analyses focused on correlations between scallop catch rates and SST and Chl-a. Above average winter SST was negatively associated with scallop catch rates over the months that followed. Associations with Chl-a were inconsistent, compared to earlier analyses by Courtney et al. (2015), which found a significantly high correlation of 0.85 between November standardised commercial catch rates and Chl-a in June (five months earlier). This initial correlation was based on relatively few years of observations (2002–2013; n=12) due to the relatively short time series for the available Chl-a data, which were from the MODIS Aqua satellite that was launched in May 2002. The correlation was confirmed using updated catch rates and Chl-a data from 2014, but the relationship was much weaker when additional data from 2015 and 2016 were eventually included.

The designed population models tested the long-time series of winter SSTs. The scale of increase in sea surface temperatures (SST anomalies) over years was not immense, and the Queensland scallop fishery does not appear to have endured high SST anomalies like the 2010–2012 marine heat wave event in Western Australia (Caputi et al., 2014). Results were most sensitive to the assumption of natural mortality, and related SST effects.

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 overly ascribed to SST, rather than to other elements of the model. However, the falling abundance could well be due to another undocumented environmental effect, or a greater effect of fishing than the model estimated. The latter could be revealed by a lower natural mortality rate than Dredge (1985).

The modelled consequence of increased SST was for reduced scallop survival, abundance and fishery yield. This result, in the context of future fishery management and harvest strategies, suggested harvest/effort control rules might need allowance for high natural mortalities, in order of 8% per month suggested by the range change in M. This is an important consideration, given that many years in the last two decades experienced above average winter SSTs.

The stock assessment can suitably describe scallops with and without the SST data. The simpler non-spatial and non-temperature model herein, together with suitable target reference points and harvest/effort control rules, could effectively manage the fishery. Verification of any management procedures is best through Management Strategy Evaluation (Punt et al., 2001; Punt et al., 2016).

In addition to this advice, estimates of natural mortality are soon to be revised, and potentially lowered, by FRDC project 2017-048. This may suggest saucer scallops are longer-lived and that measures of fishing mortality are higher than estimated previously and herein, therefore better explaining the declines in catch rates pre-1988. Lower estimates of natural mortality will change the research assumptions. Irrespective, scallops have a strong spawner-recruitment relationship, and historical fishing has played a key role in the stock's depletion. Clearly, many years of harvest were greater than MSY reference points, and at times the data suggested extreme harvest rates. Management procedures need to ensure a sufficient winter spawning stock remains each year to support the scallop population and fishery.

6.2 Saucer scallop population size and results for management procedures.

The results from the non-spatial model analysis suggested the 2018 region 3 spawning biomass was at 22% (95% confidence interval 17–32%) of virgin level in 1956 (Figure 33). Broader uncertainty was revealed by comparing model analyses, having different structural setups and assumptions. The greater uncertainty in results suggested the 2018 region 3 spawning biomass was below 40% of virgin levels in 1956 (Figure 34) (considering 95% confidence intervals around predictions were generally -5% and +10% on estimates). The results indicate that the scallop spawning population size was less than spawning levels for MSY at 45%.

The population results provide support for the new improved Queensland Government management procedures. For 2018, the precautionary result suggested up to 160 t of scallop meat was a sustainable harvest from region 3. After heavy fishing, minimal stock appeared to be present in 2018 off K'gari. From the reference points and model projections, around 84 000 effort units will lead to higher biomass to achieve the Sustainable Fisheries Strategy ecological objectives. The effort units equate to about 1500 boat-days, scaled to the potential fishing power of the fleet.

To improve management procedures, settings of recommended biological catches (RBC) and fishing efforts need to weigh up the uncertainty and risk levels in results, confirm a target reference point, and ensure from model projections that any RBC will produce increasing spawning biomass for the short term. This is critical given scallop spawning biomass is depleted below the MSY biomass level.

Currently, no Queensland Government policy defines a harvest control rule for rebuilding/increasing fished population biomass. The Australian Government (2007) and Sainsbury (2008) provide example guidance, and suggest rebuild times based on considering the life history characters of the fished species. The Australian Government (2007) summarises:

- Typically, recovery times are the minimum of 1) the mean generation time plus ten years, or 2) three times the mean generation time. Note that the mean generation time is the average age of a reproductively mature animal in an unexploited population. For saucer scallops, the mean generation time is about 1.5 years.
- Further, for stocks above B_{LIM} (20% spawning biomass ratio), but below the level that will produce maximum sustainable yield (B_{MSY}), it is necessary first to rebuild stocks to B_{MSY}. Once stocks are above B_{MSY}, rebuilding shall continue toward the target biomass B_{TARG}. However, the rate of rebuilding may be slower and shall be determined in a way that considers the appropriate balance between short-term losses and longer term economic gains.

Reference points for MSY indicated catch rates below 25 baskets per boat-day, as a threshold, gauged poor abundance of scallops on the ground. This measure can allow fishers to judge the cost/benefit of fishing in different areas and times, as well as for management to monitor within year trends of the fishery to tailor appropriate harvest control rules.

The project, methods and results feed directly into the design of the Queensland Government's proposed model-based harvest strategy for scallops. Use of the non-spatial age-based assessment herein, provides the best rapid and repeatable assessment methodology to produce a harvest control rule (e.g. like the rules by the Australian Government (2007)). The estimated recommended biological catches and fishing effort are the best available advice on what sustainable fishing pressure is for the scallop population.

7 Implications

Adoption of the findings and recommendations may result in the following:

1. Outputs of the project will inform new management procedures; which are happening under the Queensland Government's Sustainable Fisheries Strategy. Fishers will need to operate under new rules. Use of the advice herein, may result in a doubling of current fishery yields from below 200 t to near 400 t in future years.
2. An opportunity for fishers to improve planning and profitability of their fishing operations, through an understanding of expected current and future harvests. Use of results will help to produce and maintain higher catch rates than would otherwise occur.
3. Recognition of improved fishery sustainability for domestic and overseas marketing.
4. Industry are now more aware that elevated sea surface temperatures may reduce scallop abundance, catch rates, landings and profits.
5. Short-term model forecasts indicate that past levels of harvest > 400 t are unlikely. This needs to be considered by fishers and processors, and the fishery managers in regard to managing effort and the number of licensed vessel operators.

In terms of outcomes from the research, fishery managers have been involved directly through discussions with project staff and through the project's joint steering committee meetings. Outcomes will be realised post-project, and strengthened from inputs from the trawl-working group.

8 Recommendations

Based on findings from this study, further research and other activities needed to improve and develop management of the scallop fishery include:

1. Management procedures need to control fishing efforts to increase scallop biomass.
2. Maintain closure of the SRAs in the short-term until some spawning recovery is measured. If SRAs are reopened in the future, then re-evaluate the length of closed seasons (how long they need to be open and closed). It appears scallop abundance increases proportionally to the closed duration, and past modelling suggested closure times of at least three years (Campbell et al., 2010a). This signal was in the survey density estimates.
3. Update estimates of natural mortality and growth, using all historical tagging data and new results from FRDC 2017-048.
4. 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.
5. Monitor, assess and report on sea surface temperature/ocean anomalies, and consider forecasts in management discussions. Consider deployment of site-specific sea-floor water temperature sensors.
6. Review the time-series data on trawl fishing power through compulsory logbook gear sheets. The impact of improved technology is an important consideration for standardising indicators of abundance (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.
7. Continue to evaluate and improve the time series of standardised catch rates. 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 indices of abundance. 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.
8. Further work on model projections and management strategy evaluations may be required.

9 Further development

Further estimation of scallop recruitment deviations is required to develop the spatial stock model. Time prevented this, and the methods are below.

The model has enough catch rate data to fit one recruitment deviation per year, covering all areas. The biomass, which ultimately depends on the recruitment, is fitted to catch rates, for which there is already an error structure.

The standard interpretation is that the error in fitting catch rates is composed mainly of experimental error in the catch rates (i.e. the error is primarily in the catch rates, not the recruitment). A major point is that it actually makes no difference to the model-fitting procedure if it is instead assumed that the error is due to regional deviations in recruitment (i.e. it is primarily in the recruitment, not the catch rates).

To make this work, total biomass in each year (summed over all areas) needs to match the overall catch rate in that year. Then the total spawning biomass will be accurate. This is only needed for the stock–recruitment relationship, because the spawning biomass is summed over all areas.

A straightforward way to achieve this match of predicted biomass to observed catch rates in each year is to use a Poisson quasi-likelihood instead of the lognormal likelihood in the model's catch-rate matching.

The detail below provides the formulae for the Poisson quasi-likelihood for catch-rate matching.

Note also that there may be a case to do a separate analysis covering just region 3 (i.e. excluding K'gari). Oceanographic modelling suggests that the spawning stock in the K'gari zone might not seed other zones (Courtney et al., 2015). If so, the population spanning the other zones could be analysed separately from K'gari.

Poisson negative log-likelihood for matching biomass to standardised catch rate.

Notation

$x_{i\,k}$ = standardised catch rates at time step i in area or zone k before scaling to biomass; *note time steps should be the same in each area*.

s_k = scale factor for standardised catch rates in area or zone k to convert them to units of biomass

$y_{i\,k}$ = standardised catch rates after scaling to biomass, = $x_{i\,k}/s_k$

σ = dispersion parameter for converted catch rates (*does not depend on area or zone*)

$\hat{\sigma}$ = estimator of σ

n_k = number of catch rates in area or zone k (*should be the same for each area or zone*)

ν_k = degrees of freedom for catch rates in area or zone k, = n_k minus number of parameters estimated, generally = $n_k - 1$ to account for estimation of s_k.

$\mu_{i\,k}$ = predicted biomass from population model at time step i in area or zone k

$\hat{\mu}_{ik}$ = maximum likelihood estimator of $\mu_{i\,k}$ from the population model

-LL = negative log-likelihood

Recap on the lognormal model

$s_k = \exp\left\{ \sum_{i=1}^{n} (\log x_{i\,k} - \log \mu_{i\,k}) \Big/ n_k \right\}$, makes the geometric mean of $y_{i\,k}$ match that of $\mu_{i\,k}$.

$\hat{\sigma} = \sqrt{\sum_k \sum_{i=1}^{n_k} (\log y_{i\,k} - \log \mu_{i\,k})^2 \Big/ \sum_k \nu_k}$.

$\text{NLL} = \sum_k \sum_{i=1}^{n_k} \left[\log \sigma + \tfrac{1}{2}\left(y_{ik} - \mu_{ik}\right)^2 \big/ \sigma^2 \right]$ which, after we substitute $\hat{\sigma}$ described in Haddon (2001) into the likelihood and substitute ν_k for n_k, comes to $\left(\sum_k \nu_k\right) \log \hat{\sigma}$. Some users would use n_k instead of ν_k, that is, fail to correct for the number of parameters that have to be estimated.

Formulae for the Poisson model

$s_k = \sum_{i=1}^{n} x_{i\,k} \Big/ \sum_{i=1}^{n} \mu_{i\,k}$, makes the *arithmetic* mean of $y_{i\,k}$ match that of $\mu_{i\,k}$.

$\hat{\sigma} = 2 \sum_k \sum_{i=1}^{n_k} y_{i\,k} \log\left(y_{i\,k} / \mu_{i\,k}\right) \Big/ \sum_k \nu_k$, provided the above scaling has been done to make $\sum_{i=1}^{n} y_{i\,k} = \sum_{i=1}^{n} \mu_{i\,k}$. The term involving $\log y_{i\,k}$ is defined to be zero when $y_{i\,k} = 0$. The equation corresponds to estimating the dispersion parameter by the mean deviance, as is commonly done in generalised linear models.

$\text{NLL} = \sum_k \sum_{i=1}^{n_k} \left[\tfrac{1}{2} \log \sigma + \left\{ \mu_{ik} - y_{ik} + y_{ik} \log\left(y_{ik} / \mu_{ik}\right) \right\} \big/ \sigma \right]$. After we substitute $\hat{\sigma}$ into the likelihood and ν_k for n_k, this reduces to $\tfrac{1}{2}\left(\sum_k \nu_k\right) \log \hat{\sigma}$.

The term $\tfrac{1}{2}\log \sigma$ is inserted to make the maximum likelihood estimator of σ simplify to the mean deviance. Although technically this is a quasi-likelihood rather than a proper likelihood, it can also be derived from a large-sample approximation of the Poisson likelihood (see below).

The advantage of the Poisson model

The major advantage of the Poisson model is that maximum likelihood estimates of biomass exactly satisfy the equation

$$\sum_k \hat{\mu}_{i\,k} = \sum_k y_{i\,k} \, , \qquad (1)$$

provided that the population model includes a recruitment deviation at each time step *i* and the biomasses are not fitted to any data in addition to the catch rates. The lognormal model does not satisfy this equation.

A similar equation applies if recruitment deviations apply to aggregates of time steps, that is, the time step may be monthly but the recruitment deviation may be annual. If *I* is a set of time steps within a year, then, instead of equation (1), we will have

$$\sum_{i \in I} \sum_k \hat{\mu}_{i\,k} = \sum_{i \in I} \sum_k y_{i\,k} \, . \qquad (2)$$

Again the total biomass, this time averaged over the year, will be matched.

Equations (1) and (2) make the model's total biomass accurate in the case that:

- regional recruitment deviations are present but not explicitly modelled and
- the scaled, standardised catch rates $y_{i\,k}$, rather than being subject to large experimental errors, accurately represent abundance.

The accuracy of the biomass in turn ensures that there are no major errors in the model's spawning stock biomass and subsequent recruitment.

It is true that catch rates are assumed to represent exploitable biomass, which may differ from spawning stock size, and this difference can affect the accuracy of this method. For animals such as scallops there should be little difference. Inclusion of additional data such as survey catch rates (including small scallops from the previous age-class) and survey length-frequency distributions could also produce some inaccuracies in equation (1). Again these should be small if the amount of additional data is small.

Derivation of the -LL from the Poisson likelihood

For an integer variate $y \sim P(\mu)$, the Poisson likelihood is

$$\text{lik} = \exp(-\mu)\,\mu^y / y!\,.$$

For inclusion of the dispersion parameter σ and non-integer values of x_i, the likelihood becomes

$$\text{lik} = (1/\sigma)\exp(-\mu/\sigma)(\mu/\sigma)^{y/\sigma} / \Gamma(y/\sigma + 1),$$

where the factor of $1/\sigma$ accounts for the change in spacing of the discrete values of y when they are scaled by σ.

We use Stirling's formula, which is $\Gamma(x+1) \sim \sqrt{2\pi x}\, x^x e^{-x}$ as $x \to \infty$. Then

$$\text{lik} \propto (1/\sigma)\exp(-\mu/\sigma)(\mu/\sigma)^{y/\sigma} \Big/ \left\{(y/\sigma)^{y/\sigma+\frac{1}{2}} \exp(-y/\sigma)\right\}.$$

Ignoring the factor $y^{½}$, which depends on data only, this becomes

$$\text{lik} \propto \left(1/\sqrt{\sigma}\right)\exp\{(y-\mu)/\sigma\}(\mu/y)^{y/\sigma}\,,$$

which matches the formula above for the negative log-likelihood.

10 Extension and Adoption

The project was, and will continue to be, extended and communicated to the end users, such as fishery managers, other researchers, industry, and where applicable the broader community.

The direct beneficiaries of the research are Fisheries Queensland, the trawl management working group, and industry.

The research provided a number of benefits, and updated our understanding and expectations of the scallop fishery. Principally, this was:

- Detailed specifications for future stock assessment and management strategy evaluations. This will enable Government and industry to better invest in fishery dependent and survey data, improve fishery production, and contribute to co-management through a harvest strategy framework (HS).
- Aspects herein have, and will continue to help harvest strategy design. This includes improved information for indicators, reference points and harvest control rules.

Scallop survey results (sister project FRDC 2017-048) and data analyses from this project were presented to the Queensland Government's Sustainable Fisheries Expert Panel on 18/4/2018 (Department of Agriculture and Fisheries, 2018).

Discussions of results from both projects against their objectives (FRDC 2017-048 and 2017-057) occurred at the joint project steering committee meetings. The last meeting was at the Brisbane Airport Novotel on the 14/12/2018. Members of the committee include fishers, processors, Fisheries Queensland, the Great Barrier Reef Marine Park Authority, scientists from DAF, Department of Environment and Heritage Protection, James Cook University (JCU), and Western Australia Department of Fisheries.

A combined extension strategy for the associated scallop projects FRDC 2017-057 and FRDC 2017-048 was developed. As the two projects are working in collaboration there was no benefit in developing two separate extension strategies. Public extension of all scallop results is to occur by FRDC 2017-048, at the end of the project.

To date, the field-based project FRDC 2017-048 has led findings and communications. In this regard, scallop survey results are with Fisheries Queensland, and the associated expert panel and the trawl working-group.

Progress:

1) Method 1: Milestone reports – were available to the FRDC, Fisheries Queensland and the DAF trawl working-group.

2) Method 2: Media release – No media release has been actioned to date. Extension of the project to stakeholders commenced at the first project steering committee meeting on 7/9/2017. Soon after DAF was in caretaker mode for the State election, and Departmental communications were restricted until January 2018. Scallop survey results are now public, and have been presented to the DAF expert panel and trawl working group. Fisheries Queensland are reviewing the survey results for fishery management in 2019. No formal media release is appropriate at this time and communications are to be actioned by Fisheries Queensland as soon as appropriate – aligning with the report publication.

3) Method 3: FRDC website or Facebook – no results or data are appropriate to release at this time. This extension method will be actioned only after direction from the FRDC, DAF and UQ, in conjunction with FRDC 2017-048 investigators. Significant findings will be disseminated through social media (e.g. FRDC Facebook) as approved by FRDC, Fisheries Queensland and UQ at the end of the project; along with Method 4 - Presentation of final results and recommendations.

Presentation of final project findings, by Dr W.-H. Yang, was at the Southern Inshore Trawl Region Harvest Strategy Workshop 23-24 May 2019. The workshop was at the Hervey Bay Boat Club. There were about 16 fishers and processors present, many of whom raised points and questions. Overall, industry appreciated the work. The main scientific focus from industry was how we define a scallop boat-day, and how this subsequently affects the standardised catch rate time-series.

Dr W. Yang presented mathematical aspects of the scallop modelling to the ‘Biometrics by the Boarder’ meeting in Kingscliff 2017, and the Satellite Workshop Applied^2 Probability event hosted by CARM, UQ in 2019.

Dr. M. O’Neill presented at the August 2019 Trawl Working Group.

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12 Appendices

12.1 Data zones, areas and rules

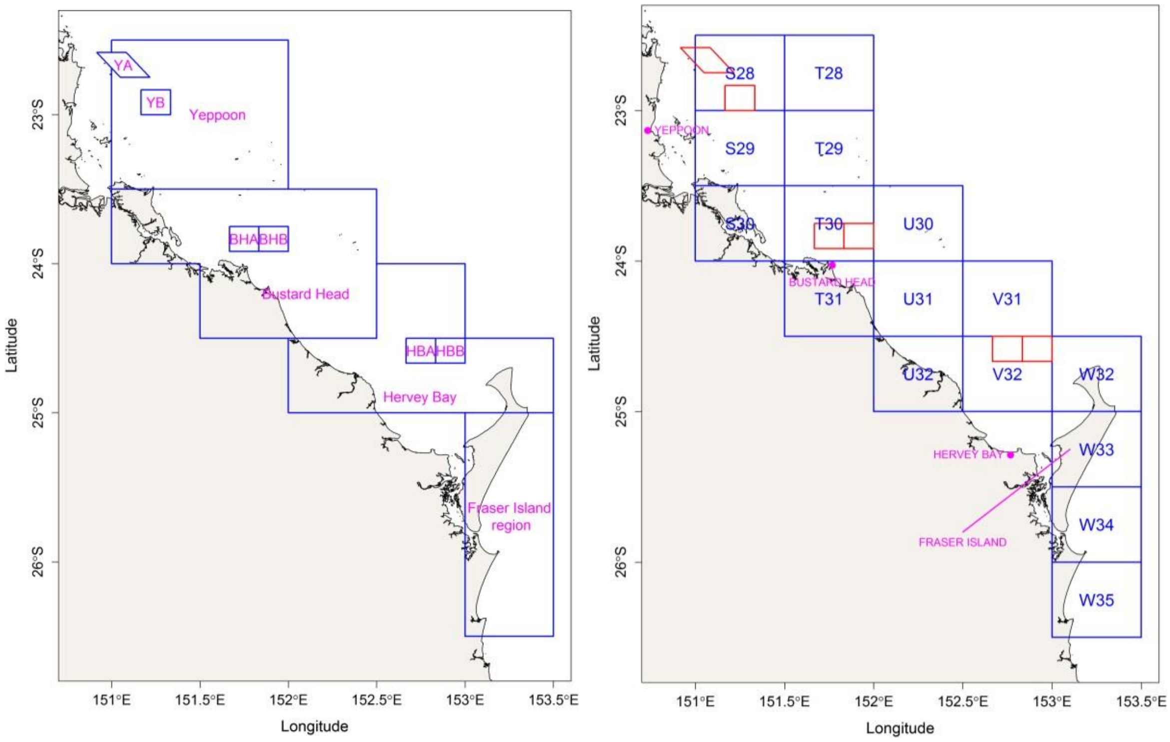


Figure 42. Spatial stratification of ten areas for the harvest data and the scallop population model (left figure), and the right figure illustrates the corresponding logbook grids.

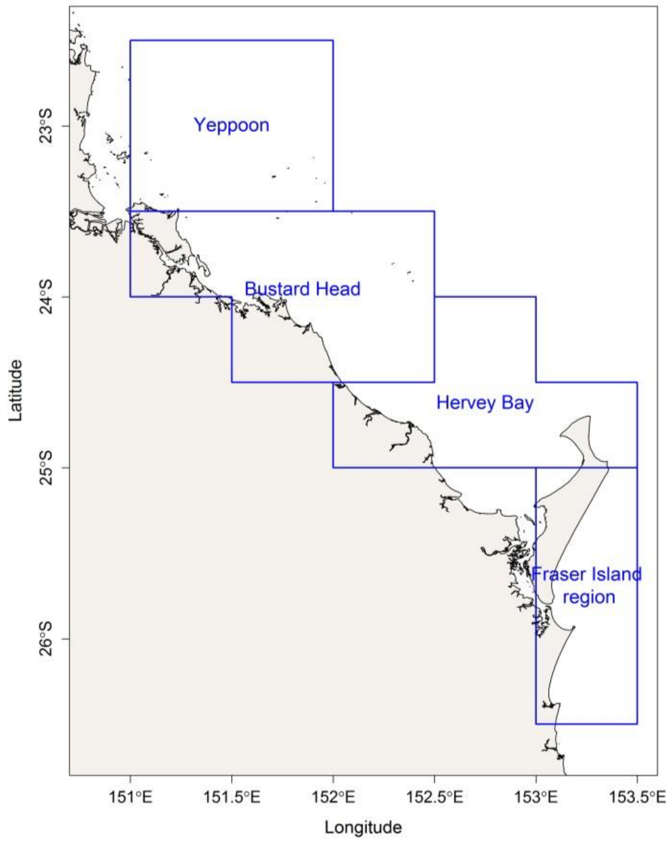


Figure 43. Spatial stratification of four zones for the catch rate analyses.

Table 14. Historical commercial scallop data, (Dredge, 2006).

Data	Details	Notes
Time period	1.1.1956–31.12.1987	
Records	Annual records were by calendar year.	
Harvests	Meat weight was in tonnes.	Converted to baskets using the conversion from Table 29.
Spatial coverage	Aggregated to cover the main fishing waters of east-coast latitudes south of 22° S inclusive and north of 27° S inclusive.	Trawling for scallops commenced in the mid-1950s off the central Queensland coast, between 23° S and 25° S (Ruello, 1975). While more than 90% of average annual scallop landings were taken from these latitudes, grounds in the vicinity of Hydrographer's Passage (just north of 22° S) received intermittent recruitment and occasionally produced commercial quantities of saucer scallops (Dredge, 2006).

Table 15. HTrawl logbook catch rates. The scallop data were voluntary daily records per vessel between 1977 and 1987, prior to the implementation of the compulsory CFISH logbook system in 1988. Table 8.3.7.1 in Project No 1999/120 (O'Neill et al., 2005) provides a description of historical trawl data sources and location of the data.

Data	Details	Notes
Time period	1.1.1977–31.12.1987	
Records	Daily records per vessel.	
Harvests	Baskets of scallops.	Baskets used.
Logbook grids.	S28, S29, T28, T29 (Yeppoon), S30, T30, T31, U30, U31 (Bustard Head), U32, V31, V32, W32 (Hervey Bay), W33, W34, W35 (K'gari).	Previous projects used HTrawl data (O'Neill et al., 2005; O'Neill and Leigh, 2006; Yang et al., 2016).

Table 16. Queensland commercial logbook data (CFISH).

Data	Details	Notes
Time period	1.1.1988–30.10.2018	
Records	Daily records per vessel.	
Harvests	Baskets of scallop.	Baskets used.
Area	This covered the main fishing waters of east-coast latitudes south of 22° S inclusive and north of 27° S inclusive, and east of 149° E and west of 154° E inclusive.	
Species codes	Caabspeciesid = 23270000 (scallop – unspecified), 23270001 (scallop - saucer), 23270003 (scallop - mud) and 23270005 (scallop - queen).	Identified scallop for calculating harvests.
Logbook grids for catch rate analysis	S28, S29, T28, T29 (Yeppoon), S30, T30, T31, U30, U31 (Bustard Head), U32, V31, V32, W32 (Hervey Bay), W33, W34, W35 (K'gari).	These grids represented ≥ 95% of the total scallop effort.
Fishing method codes	FishingMethodID=7, 37	Identified otter trawling.

Table 17. TrackMapper data (Good et al., 2007; Courtney et al., 2016).

Data	Details	Notes
Time period	1.11.2000–30.10.2018	
Harvest and effort records	Records for baskets of scallops and hours fished.	VMS supplied the effort data.
Area	Single area: this covered the main fishing waters of east-coast latitudes south of 22° S inclusive and north of 28° S inclusive, and east of 149° E and west of 154° E inclusive.	
Species codes	Caabspeciesid = 23270000 (scallop – unspecified), 23270001 (scallop - saucer), 23270003 (scallop - mud) and 23270005 (scallop - queen).	Only minor harvests were against the non-saucer scallop codes.
Start time	Exact. Start time = 0, End time = 24 hours	
Spatial resolution	0.6 minute (1.1 km).	
Vessel speed	Between 0.9 m/s (1.8 knots) and 1.8 m/s (3.5 knots).	Trawling was between these speeds.
Catch selection	> 0	The scallop catch can be any component of the fisher's daily catch record, including records where scallop was a minor component of the catch.

Table 18. Proportions of harvest by month and seven areas, from the GLM on HTrawl catch rates 1977–1987.

Calendar month	Yeppoon (excluding S28)	S28	Bustard Head (excluding T30)	T30	Hervey Bay (excluding V32)	V32	K'gari
1	0.03896	0.02771	0.03497	0.02814	0.00106	0.01726	0.00049
2	0.03493	0.01540	0.02139	0.01592	0.00256	0.01229	0.00046
3	0.00789	0.02061	0.03372	0.01247	0.00038	0.00986	0.00002
4	0.00864	0.00561	0.00572	0.01512	0.00727	0.00889	0.01183
5	0.00584	0.00713	0.00467	0.00578	0.00014	0.00358	0.00276
6	0.00412	0.00215	0.00904	0.01052	0.00469	0.00375	0.00036
7	0.00455	0.00510	0.01459	0.01213	0.00155	0.00488	0.00064
8	0.00774	0.01547	0.02270	0.02102	0.00385	0.00732	0.00049
9	0.01251	0.00310	0.00795	0.01504	0.00051	0.02760	0.00169
10	0.02038	0.00976	0.01079	0.04097	0.00455	0.01088	0.00008
11	0.03757	0.01285	0.01984	0.03479	0.00470	0.01228	0.00171
12	0.04366	0.01731	0.02274	0.02371	0.00827	0.00776	0.00086

The over-dispersed Poisson GLM, applied to the HTrawl data 1977–1987 (Table 15), gave the proportion of baskets harvested by fishing month and area, where area was defined by Yeppoon (excluding grid S28), grid S28, Bustard Head (excluding grid T30), grid T30, Hervey Bay (excluding grid V32), grid V32 and K'gari (Table 18). The proportions in Table 18 divided the historical data (Table 14) by areas and months. The monthly proportions were from TrackMapper.

Table 19. Monthly proportions of harvest in SRA and non-SRA areas for the logbook grids S28, T30 and V32.

Calendar month	S28			T30			V32		
	Non-SRA	YA	YB	Non-SRA	BHA	BHB	Non-SRA	HBA	HBB
1	0.4116	0.1045	0.4839	0.1019	0.5169	0.3813	0.0743	0.8805	0.0452
2	0.3799	0.5313	0.0888	0.3263	0.0553	0.6184	0.529	0.1511	0.3198
3	0.6411	0.3045	0.0543	0.6145	0.0837	0.3018	0.6438	0.3331	0.0232
4	0.7143	0.2176	0.0682	0.5014	0.1656	0.333	0.5731	0.3725	0.0545
5	0.9173	0.0134	0.0693	0.3005	0.0615	0.638	0.5273	0.4402	0.0325
6	0.8406	0.0808	0.0786	0.0692	0.7895	0.1413	0.6835	0.2861	0.0304
7	0.9052	0.0686	0.0263	0.1835	0.6519	0.1646	0.5539	0.3708	0.0753
8	0.9405	0.0528	0.0067	0.3132	0.3155	0.3713	0.4873	0.4558	0.0569
9	0.8421	0.011	0.1469	0.3217	0.363	0.3153	0.4639	0.5031	0.033
10	0.8421	0.011	0.1469	0.3217	0.363	0.3153	0.4639	0.5031	0.033
11	0.4116	0.1045	0.4839	0.1019	0.5169	0.3813	0.0743	0.8805	0.0452
12	0.4116	0.1045	0.4839	0.1019	0.5169	0.3813	0.0743	0.8805	0.0452

TrackMapper calculated the 12-month proportions of harvests among the SRAs and non-SRA areas of a grid (Table 19). The six nested SRAs were in three of 30 min x 30 min grids: YA and YB are in S28; BHA and BHB in T30; HBA and HBB in V32. Each grids harvest divided into two SRA areas and one non-SRA area. The 12-month proportions of the three areas of a grid used data from fishing years 2001 to 2018. For each month, the proportion of an area of a grid was the ratio of the mean of the area over the sum of the three catch means of the grid (Table 19). The monthly proportion of harvest in SRA and non-SRA areas in Table 19, were applied to the harvest from the Queensland commercial logbook data to transform the harvest data 1988–2018 into ten areas as defined in Figure 42.

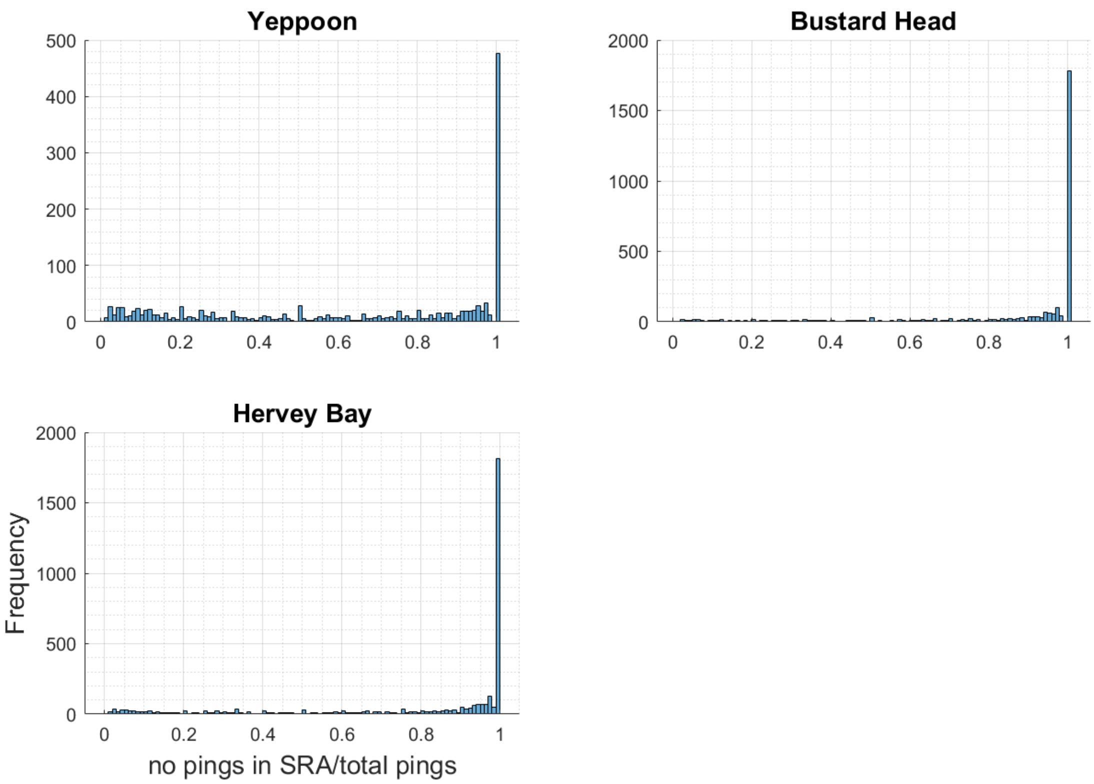


Figure 44. Proportion of each vessels' daily fishing effort inside open SRAs. The proportions represent the number of VMS pings within SRAs compared to the total number of pings for the day. Data was from TrackMapper (VMS data). The frequency is the count of the number of boat-days with a proportion.

12.2 Sensitivity analysis

Table 20: Phase settings for the model parameters. Four optimization procedures were conducted: Procedure 1, 2, 3 and 4. In an optimization procedure, the given number for a parameter indicates the phase of the ADMB optimization procedure, i.e. when the parameter will be included in the optimization procedure. Note that (range) represents a specified parameter space for a parameter where the ADMB optimization process will explore.

Parameter	Meaning	Procedure 1 (range)	Procedure 2 (range)	Procedure 3 (range)	Procedure 4 (range)
θ	von Mises distribution measure of location – recruitment pattern.	3 (-∞, ∞)	2 (-∞, ∞)	3 (-∞, ∞)	3 (-∞, ∞)
κ	von Mises distribution measure of concentration – recruitment pattern.	6 (10^{-4},10^{2})	6 (10^{-4},10^{2})	7 (10^{-4},10^{2})	6 (-∞, ∞)
ξ	Steepness h is a function of ξ; that is, $h = \frac{1.1+\exp(\xi)}{5+\exp(\xi)}$.	1 (-10,10)	2 (-10,10)	6 (-10,10)	1 (-10,10)
γ_k	$R_{0,k}$ is recruitment in virgin years in zone k and formulated as a function of γ_k; $R_{0,k} = \exp(\gamma_k) \times 10^9$.	1 (-∞, ∞)	1 (-∞, ∞)	1 (-∞, ∞)	1 (-∞, ∞)
η_y	Annual recruitment deviations of fishing years 1988-2018.	2 (-∞, ∞)	3 (-∞, ∞)	2 (-∞, ∞)	2 (-∞, ∞)
β_M	Winter sea surface temperature effect on natural mortality	4 (-∞, ∞)	4 (-∞, ∞)	4 (-∞, ∞)	4 (-∞, ∞)
γ_{qk}	Intercept for catchability in zone k.	5 (-∞, ∞)	5 (-∞, ∞)	5 (-∞, ∞)	5 (-∞, ∞)
γ_{jan}	Closure effect on catchability.	5 (-∞, ∞)	5 (-∞, ∞)	5 (-∞, ∞)	5 (-∞, ∞)
$\gamma_{q^{(s0+)}}$	Catchability of 0+ scallop $q^{(s0+)} = \exp(\gamma_{q^{(s0+)}})$	5 (-∞, ∞)	5 (-∞, ∞)	5 (-∞, ∞)	5 (-∞, ∞)

Table 21: Five sets of initial values for the model parameters. Initial values for spatial and temporal parameters (i.e., γ_k, η_y and γ_{qk}) were generated from Gaussian distributions randomly. For those parameters, the distributions are presented instead of generated values.

Parameter	Set 1	Set 2	Set 3	Set 4	Set 5
θ	8.81	8.81	8.81	7.00	7.00
κ	4.81	4.81	4.81	5.00	5.00
ξ	1.1	1.1	1.1	1.03	1.03
γ_k	$N(0,1)$	$N(0,1)$	$N(0,1)$	$N(0,1)$	$N(0,1)$
η_y	$N(0,1)$	$N(0,1)$	$N(0,1)$	$N(0,1)$	$N(0,1)$
β_M	0	0	0	0	0
γ_{qk}	$N(0,1)$	$N(0,1)$	$N(0,1)$	$N(0,1)$	$N(0,1)$
γ_{jan}	0	0	0	0	0
$\gamma_{q^{(s0+)}}$	-3.91	-3.91	-3.91	-3.91	-3.91

12.3 GenStat REML code and catch rate settings

Table 22. GenStat code used to predict saucer scallop standardised catch rates 1988–2018, analysis 1.

```
VCOMPONENTS [FIXED=
fishyear*fishingmonth*area+loghours+loghp+logspeed+sonar+gps2+nettype+ggear4+boards;
FACTORIAL=2]\ RANDOM=boat_mark+grid; INITIAL=1; CONSTRAINTS=positive

REML [PRINT=model,components,deviance,waldTests;\ PSE=allestimates; MVINCLUDE=*;
method=ai;] logn

vpredict [print=description,predictions,se; PRED=Lnormym; SE=LnormymSE]
fishyear,fishingmonth,area, ggear4,nettype,gps2,sonar,loghp,loghours2,boat_mark;
levels=*,*,*,!(1),!(3),!(1),!(1),!(5.843),!(2.508),!(42)
```

For prediction, the fixed term variables were set as outlined in Table 23. Boat number 42 matched the maximum annual-average fleet-vessel effect. This was in 2007. Thus, the vessel with a log parameter value closest to 0.11586, which was boat 42, set the vessel term for prediction. These settings defined predictions according to a modern vessel-fleet profile. This was to ensure the catchability scale for catch rates was appropriate, i.e. set to the historical best (modern) fleet, for deriving fishery reference points.

Table 23. Values of REML fixed terms for predicting standardised catch rates 1988–2018, analysis 1.

Term	**Set to**	**Reason**
Ground gear	Drop chain	Most popular ground gear.
Net type	Quad gear	Since 2007, there was a shift to using quad gear.
GPS	Using GPS	Most vessels used GPS by the late 1990s.
Sonar	Using sonar	Sonar was associated with vessels with higher harvests.
log(hours)	2.508	Based on the mean of log hours fished per vessel-night 2007–2018. This was 12.28 hours.
log(HP)	5.822	Yearly mean of 2018 log(engine horse power HP). This was 337 HP.

Table 24. GenStat code used to predict saucer scallop standardised catch rates 1977–2018, analysis 2.

The numbers for offsetting fishing power (offsetlog) were from the linear predictors for HP, sonar, GPS, net type and ground gear from the REML model analysis 1, 1988–2018, in Table 22. The variable loghours in the vpredict command was set 2.508, as explained in Table 23. Boat 23 implied the log boat/fleet effect of 0.1335.

The gear data 1977–1987 represented vessels having a standard flat otter board (board type 1, zero effect), drop chain ground gear (gear 1, zero effect), triple otter trawls (gear 3), no GPS and 12.4% presence of sonar. Vessel HP data were available. These datasets were collated under FRDC Project No 1999/120 (O'Neill et al. 2005) and then 2006/024 (O'Neill and Leigh 2006; Campbell et al. 2010). Table 8.3.7.1 in Project No 1999/120 (O'Neill et al. 2005) provides a description of historical trawl data sources and descriptions and indicates a pathway to the data.

‘Source: z DataSourcesQry in w-research\FRDC1999120\cfish&cls\AllTrawl.mdb’.

```
"Take parameter estimates from 1988...2018 reml analysis"

calculate offsetlog =
loghp*0.38869+sonar*0.18492+gps2*0.0457+(nettype.eq.3)*0.2994+(nettype.eq.4)*0.2323+(nettype.eq.5)*0.2666+(ggear4.eq.3)
*0.048356+(ggear4.eq.4)*-0.060586+(ggear4.eq.5)*-0.27314

calculate lognoffset=logn-offsetlog

VCOMPONENTS [FIXED= fishyear*fishingmonth*area+loghours; FACTORIAL=2]\
RANDOM=boat_mark; INITIAL=1; CONSTRAINTS=positive
REML [PRINT=model,components,effects,deviance,waldTests;\
 PSE=allestimates; MVINCLUDE=*; method=ai;] lognoffset


vpredict [print=description,predictions,se; PRED=Lnormym; SE=LnormymSE] fishyear,fishingmonth,area,\
loghours,boat_mark;\
levels=*,*,*,!(2.508),!(23)
```

Table 25. Genstat code used to predict saucer scallop standardised catch rates, analysis 3. The variables in the fixed terms were set as outlined below in Table 26. Boat mark 206 matched the 2007 fishing fleet, with a log effect of 0.104.

```
VCOMPONENTS [FIXED= fishyear*fishingmonth+loghours2+loghp+sonar+gps2+nettype+ggear4; FACTORIAL=2]\
            RANDOM=boat_mark+grid; INITIAL=1; CONSTRAINTS=positive
REML [PRINT=model,components,effects,deviance,waldTests;PSE=allestimates; MVINCLUDE=*; method=ai;] logn

vpredict [print=description,predictions,se; PRED=Lnormym; SE=LnormymSE] fishyear,fishingmonth,\
ggear4,nettype,gps2,sonar,loghp,loghours2,boat_mark; levels=*,*,!(1),!(3),!(1),!(1),!(5.867),!(2.4964),!(206)
```

Table 26. Values of fixed terms in the REML for predicting standardised catch rates 1988–2018, analysis 3.

Term	**Set to**	**Reason**
Ground gear	Drop chain	Most popular ground gear.
Net type	Quad gear	Since 2007, there was a shift to using quad gear.
GPS	Using GPS	Most vessels used GPS by the late 1990s.
Sonar	Using sonar	Sonar was associated with vessels with higher harvests.
log(hours)	2.4964	Based on the estimated mean of hours fished 2007–2018, which back-transformed to 12.28 hours per day.
log(HP)	5.867	Yearly mean of 2018 log(engine horse power HP). This was 353 HP.

Table 27. GenStat code used to predict saucer scallop standardised catch rates, analysis 4. The offsetlog calculation was from the linear predictors for HP, sonar, GPS, net type and ground gear. Boat mark 231 set the predictions based on the 2007 fleet, with a log effect of 0.13745.

```
"Correct predictions for offset and bias correction by using the linear predictors from the REML model for 1988–2018:"

calculate offsetlog =
loghp*0.3897+sonar*0.1861+gps2*0.02507+(nettype.eq.3)*0.3119+(nettype.eq.4)*0.2241+(nettype.eq.5)*0.1954+\
(ggear4.eq.3)*0.01670+(ggear4.eq.4)*-0.07124+(ggear4.eq.5)*-0.25040

calculate lognoffset=logn-offsetlog



VCOMPONENTS [FIXED= fishyear*fishingmonth+loghours2; FACTORIAL=2]\
RANDOM=boat_mark+grid; INITIAL=1; CONSTRAINTS=positive
REML [PRINT=model,components,effects,deviance,waldTests;\
PSE=allestimates; MVINCLUDE=*; method=ai;] lognoffset

vpredict [print=description,predictions,se; PRED=Lnormym; SE=LnormymSE] fishyear,fishingmonth,loghours2,boat_mark;\
levels=*,*,!(2.496917),!(231)

calculate predym=exp(lnormym+ems5/2+offsetlogyrv$[!(231)])

calculate predym_lowci = exp(lnormym + ems5/2 - lnormymse*1.96+offsetlogyrv$[!(231)]) "lower 95% CI"

calculate predym_upci_nz = exp(lnormym + ems5/2 + lnormymse*1.96+offsetlogyrv$[!(231)]) "upper 95% CI"
```

12.4 Population model

The scallop stock model composed of the following components: 1) dynamics population process (Table 28), parameters (Table 29) and tuning functions (Table 30) to fit the model to data. The equations and parameters were as follows:

Table 28. Equations for the age-based population dynamics.

Aged-Based Population Dynamics

Notations to represent time, space and scallop age **Equation**

- Fishing year y started from 1956 and finished in 2018. 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 756 (i.e. 12 months × 63 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.
- The scallop fishery was spatially stratified into ten areas denoted by k=1,...,10.

Number of Scallops N_{kta}:

The number of scallops N_{kta} at age a in spatial zone k at monthly time-step t was modelled with the following recursive equation,

$$N_{kta} = \begin{cases} R_{kt} & \text{for } a = 1 \\ N_{k,t-1,a-1} \exp(-Z_{k,t-1,a-1}) & \text{for } a = 2, \dots, 48 \end{cases}. \quad (1)$$

Note that N_{kta} 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_{kt}:

The number of scallops recruited R_{kt} at age group a=1 in spatial zone k at time-step t was defined as follows,

$$R_{kt} = \frac{E_{y-1}}{(\alpha_k + \beta_k E_{y-1})} \exp(\eta_y)\, \phi_t \quad (2)$$

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

Annual number of eggs E_y:

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

$$E_y = 0.5 \sum_k \sum_t \sum_a N_{kta} \times \text{Mat}_a \times \text{Fec}_a \times \text{Spawn}_t. \quad (3)$$

- 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_{kta} were females.
- Spawning from the K'gari area was not included in the overall index. Southward ocean currents do not support a recruitment linkage to the main fishing grounds Hervey Bay and north.

Recruitment pattern ϕ_t:

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

$$\phi_t = \exp(\kappa \cos(2\pi(m_t - \theta)/12)) \,/\, \sum_{m_{t'}=1}^{12} \exp(\kappa \cos(2\pi(m_{t'} - \theta))), \tag{4}$$

where m_t was the fishing month at time-step t in fishing year 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 $\sum_t \phi_t = 1$. 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.

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

Survival rate $\exp(-Z_{tak})$ at age a in spatial zone k at monthly time-step t was the product of the survival rates from monthly natural mortality M_y of fishing year y and harvest rates u_{kt}. The mathematical expression was written with the following form

$$\exp(-Z_{kta}) = \exp(-M_y)(1 - v_{ta}u_{kt}). \tag{5}$$

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

Harvest rate u_{kt}**:**

$$u_{kt} = C_{kt}/(B_{kt}^{(1)} b_t^{-1}), \tag{6}$$

where C_{kt} represented the total harvest (in baskets) in zone k at time-step t, and b_t was the converter for basket and meat weight.

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

$$B_{kt}^{(1)} = \sum_a N_{kta} w_a v_{ta}^{*} \exp(-0.5M_y), \tag{7}$$

$$B_{kt}^{(2)} = \sum_a N_{kta} w_a v_{ta}^{*} exp(-0.5M_y)\sqrt{1 - u_{kt}} \tag{8}$$

Note that $^{(1)}$ and $B^{(2)}$ were presented in kilograms. The difference between the two was that $^{(1)}$ expressed the midmonth exploitable biomass before fishing and $B^{(2)}$ the exploitable biomass in the middle of a fishing pulse. $^{(1)}$ was used to calculate harvest rates and should be large than C . $^{(2)}$ was used to connect catch rates. Use of equation $^{(1)}$ with fixed 2018 values of v^* , described biomass trends without MLS changes.

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

Vulnerabilities v_{ta} and v^* of age a at time-step t incorporated the probability density of length $f_a(\ell)$ at age a, selectivity of nets $v(\ell)$, 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_{kt}. v^* 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^* were written as

$$v_{ta} = \int_\ell f_a(\ell) v_t(\ell)(G_t(\ell, \mathrm{MLS}_t) + (1 - G_t(\ell, \mathrm{MLS}_t))d_{kt})d\ell, \tag{9}$$

$$v^* = \int f(\ell) v_t(\ell) G_t(\ell, \mathrm{MLS}_t) d\ell. \tag{10}$$

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

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

$$c_{kt}^{(f)} = q_{kt} B_{kt}^{(2)} b_t^{-1}, \tag{11}$$

$$c_{kt}^{(s_{0+})} = \frac{q^{(s_{0+})}\left(\sum_{a=1}^{48} N_{kta}\, exp(-0.5M_y) P_a(\ell \le 78mm)\right)}{A_k}, \tag{12}$$

$$c_{kt}^{(s_{1+})} = \frac{q^{(s_{1+})}\left(\sum_{a=1}^{48} N_{kta}\, exp(-0.5M_y) P_a(\ell > 78mm)\right)}{A_k}, \tag{13}$$

where q_{kt} was the catchability in zone k at time-step t, $q^{(s_{0+})}$ and $q^{(s_{1+})}$ were the catch efficiency for 0+ and 1+ scallop, respectively, and A_k was the area of zone k. The units of $c_{kt}^{(f)}$ was baskets per standardised boat-day, and $c_{kt}^{(s_{0+})}$ and $c_{kt}^{(s_{1+})}$ were numbers per hectare. Catchability q_{kt} 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 (Joll and Penn, 1990; Miller et al., 2019).

Table 29. Population model parameters and definitions.

Model parameters		
Known	**Equations and values**	**Notes**
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., 2010b).
$f_a(\ell)$	The normal probability density of length at age a, with mean ℓ_a and variance 2.285^2.	
$P_a(\ell \leq L)$	$\int_0^L f_a(\ell) d\ell$	The probability of length less than or equal to L at age a.
Mat_ℓ	$\text{Mat}_\ell = \frac{\exp(-8.72 + 0.185\ell)}{1 + \exp(-8.72 + 0.185\ell)}$	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 $\ell_a \sim (\ell_a, 2.285^2)$.
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 (3) to produce annual number of eggs.
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.
w_a	$w_a = 1.259 \times 10^{-6} \ell_a^{3.485}$	Meat weight (kg) at age a (O'Neill et al., 2005), used in Equation (7) and (8).
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).
$v_t(\ell)$	Logistic retention curves $v_t(\ell) = \frac{\exp(a_t + b_t\ell)}{1 + \exp(a_t + b_t\ell)}$	See Figure 9-4 in Campbell et al. (2010b) 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).

	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.	In effect, Courtney et al. (2008) figures 1 and 3 suggested selectivity had not changed.

$G(\ell, \text{MLS}_t)$	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., 2010b). Tumbler use was sporadic in the 1970s, but was utilised from late 1980.

d_{kt}	3.3%	Discard mortality (Campbell et al., 2010b).
A_k	429752.899 Yeppoon, 27710.890 YA, 31679.795 YB, 378212.953 Bustard Head, 315000.696 BHA, 31515.614 BHB, 264299.154 Hervey Bay, 31401.342 HBA, 30400.289 HBB, 231445.439 K'gari.	Zone k areas from monthly TrackMapper effort maps for January 2000 to April 2018, where fishing effort > 1 hour. No SRAs effort condition applied. Measured in hectares.
Unknown		
$R_{0,k}$ and h	$\alpha_k = E_0(1-h)/(4hR_{0,k})$, $\beta_k = (5h-1)/(4hR_{0,k})$, $R_{0,k} = \exp(\gamma_k) \times 10^9$, $h = \dfrac{1+\exp(\xi)}{5+\exp(\xi)}$	R_0, was recruitment in virgin years prior to fishing in zone k. 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 (4).
$\exp(-M_y)$	The survival rate of monthly natural mortality M_y for fishing year y logit $(\exp(-M_y)) = \alpha_M + x_{y-1}\beta_M$, where x_{y-1} was the winter SST deviation in fishing year $y-1$ and β_M was the associated coefficient. Note that $\text{logit}(z) = \log(\frac{z}{1-z})$, where $0 < z < 1$.	The survival rate of monthly natural mortality, M_y: $0 < \exp(-M_y) < 1$. α_M was fixed to value 2.363 so that monthly natural mortality is equal to 0.09 according to the tagging study of Dredge (1985).

	A log linear equation were also compared: $-M_y = 0.09 + x_{y-1}\beta_M$	Winter SST deviations were for 1955-2017. The reference winter SST was 21.096 °C for 1977, when Dredge (1985) tagged scallops. The mean winter SST deviation for virgin years was equal to -0.258 °C for 1900-1954.
q_{kt}	Scallop catchability composed of three components with the form: $\exp\left(\gamma_{q_k} + \gamma_{jan}\delta_{kt} + \gamma_s \cos(\frac{2\pi t}{12})\right) \times 10^{-7}$ where γ_{q_k} was spatially dependent intercept; 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 in zone k; 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). Note that δ_{kt} was equal to zero if zone k did not include SRAs.	Catchability at time-step t in zone k. Note that the seasonal effect γ_s was set to zero in the current analysis.
$q^{(s_{0+})}$	$q^{(s_{0+})} = \exp\left(\gamma_{q^{(s_{0+})}}\right)$	Catchability of 0+ scallop.

Table 30. The log-likelihood fitting functions for ADMB.

Objective function

Log likelihood functions **Equation**

Catch rates $c_{tk}^{(f)}$ of zone k:

Let $c_{tk}^{(f_o)}$ be the observed standardised catch rate for zone k at monthly time-step t. Assume that $\log(c_{tk}^{(f_o)})$ was the Gaussian distribution with mean $\log(c_{tk}^{(f)})$ and constant standard deviation $\sigma_k^{(f_o)}$. The log-likelihood function l_{c_k} was written as

$$l_{c_k} = -0.5\sum_t\left(\log(2\pi) + 2\log\left(\sigma_k^{(f_o)}\right) + \frac{\left(\log(c_{tk}^{(f_o)}) - \log(c_{tk}^{(f)})\right)^2}{\left(\sigma_k^{(f_o)}\right)^2}\right). \quad (14)$$

Here, $\sigma_k^{(f_o)}$ was replaced with the following form

$$\hat{\sigma}_k^{(f_o)} = \sqrt{\frac{\sum_t\left(\log(c_{tk}^{(f_o)}) - \log(c_{tk}^{(f)})\right)^2}{n_k^{(f_o)}}},$$

where $n_k^{(f_o)}$ was the total number of the observed standardised catch rates of zone k. Then, Equation (13) could be simplified to

$$l_{c_k} = -0.5 n_k^{(f_o)}\left(\log(2\pi) + 2\log\left(\hat{\sigma}_k^{(f_o)}\right) + 1\right). \quad (15)$$

Scallop density $c_{tk}^{(s^{0+})}$ of the 0+ group in zone k:

The October scallop survey data were available for fishing years 1998 to 2007 and 2018 to 2019. Let $c_{tk}^{(s_{0+,o})}$ be the observed scallop densities of the 0+ scallop group at time-step t of zone k. Assume that $\log(c_{tk}^{(s_{0+,o})})$ was the Gaussian distribution with mean $\log(c_{tk}^{(s_{0+})})$ and constant standard deviation $\sigma_k^{(s_{0+})}$. The log-likelihood function $l_{s_{0+,k}}$ was written as

$$l_{s_{0+,k}} = -0.5\sum_t\left(\log(2\pi) + 2\log\left(\sigma_k^{(s_{0+})}\right) + \frac{\left(\log(c_{tk}^{(s_{0+,o})}) - \log(c_{tk}^{(s_{0+})})\right)^2}{\left(\sigma_k^{(s_{0+})}\right)^2}\right).$$

Here, $\sigma_k^{(s_{0+})}$ was replaced with the following form

$$\hat{\sigma}_k^{(s_{0+})} = \sqrt{\frac{\sum_t\left(\log(c_{tk}^{(s_{0+,o})}) - \log(c_{tk}^{(s_{0+})})\right)^2}{n_k^{(s_{0+})}}}, \quad (16)$$

where $n_k^{(s_{0+})}$ was the total time points of the 0+ density of zone k. Then, Equation (15) could be simplified to

$$l_{s_{0+,k}} = -0.5 n_k^{(s_{0+})} \left(\log(2\pi) + 2\log\left(\hat{\sigma}_k^{(s_{0+})}\right) + 1 \right). \tag{17}$$

Scallop density $c_{tk}^{(s_{1+})}$ of the 1+ group in zone k:

By using the same assumption, the log-likelihood function $l_{s_{1+,k}}$ can be written as

$$l_{s_{1+,k}} = -0.5 n_k^{(s_{1+})} \left(\log(2\pi) + 2\log\left(\hat{\sigma}_k^{(s_{1+})}\right) + 1 \right), \tag{18}$$

with $n_k^{(s_{1+})}$ as the total time points of the 1+ density of zone k and $\hat{\sigma}_k^{(s_{1+})}$ as being written as

$$\hat{\sigma}_k^{(s_{1+})} = \sqrt{\frac{\sum_t \left(\log(c_{tk}^{(s_{1+,o})}) - \log(c_{tk}^{(s_{1+})}) \right)^2}{n_k^{(s_{1+})}}},$$

where $c_{tk}^{(s_{1+,o})}$ was the observed scallop densities of the 1+ scallop group at time-step t of zone k.

Midmonth exploitable biomass $B_{kt}^{(1)}$ in zone k:

C_{kt} in equation (6) represented the total catch (in baskets) in zone k at time-step t and b_t the converter for basket and meat weight (kg). Assume that C_{kt} was normally distributed with mean $B_{kt}^{(1)} b_t^{-1}$ (i.e., exploitable biomass in baskets) and constant variance $\sigma_{B^{(1)}}^2$. The total catch C_{kt} was the partially observed exploitable biomass, constrained to be less than or equal to the exploitable biomass. Otherwise, the harvest rate of equation (6) could be larger than one. Hence, the log-likelihood function of zone k was written

$$l_{B_k^{(1)}} = \sum_t \log\left(1 - \Phi\left(\frac{C_{kt} - B_{kt}^{(1)} b_t^{-1}}{\sigma_{B^{(1)}}}\right)\right), \tag{19}$$

where $\Phi(\cdot)$ was standard normal cumulative distribution function. The constant variance $\sigma_{B^{(1)}}^2$ was treated as a tuning parameter with given values. $\sigma_{B^{(1)}}^2$ was given $\exp(8) \times 10^5$.

Prior distribution (or penalty)

γ_k:

$\gamma_k \sim N(0, \sigma_{\gamma_k}^2)$, where $\sigma_{\gamma_k}^2$ was the hyperparameter with a specified value. In the analysis, all of $\sigma_{\gamma_k}^2$ were specified a constant value. $\sigma_{\gamma_k}^2$ was specified 100 as a vague prior.

ξ:

$\xi \sim N(1.1, \sigma_\xi^2)$ with mean 1.1 and variance σ_ξ^2 with a given value. With mean 1.1, the steepness h is about 0.5. The hyperparameter σ_ξ^2 was specified 1000 as a vague prior.

θ:

$\theta \sim N(8, \sigma_\theta^2)$, where σ_θ^2 was a hyperparameter with a given value. Mean equal to 8 refers to fishing month 8 (i.e., July). The hyperparameter σ_θ^2 was specified 1.

κ:

$\kappa \sim lognormal(0, \sigma_\kappa^2)$, where σ_κ^2 was a hyperparameter with a given value. The hyperparameter σ_κ^2 was specified 1. This setting gives variance to be about 4.671.

$\boldsymbol{\beta_M}$:

$\beta_M \sim MN(0, \sigma^2_{\beta_M})$, where $\sigma^2_{\beta_M}$ was a hyperparameter with a given value. The hyperparameter $\sigma^2_{\beta_M}$ was specified 100 as a vague prior.

$\boldsymbol{\gamma_{q_k}}$:

$\gamma_{q_k} \sim N(0, \sigma^2_{\gamma_{q_k}})$, where $\sigma^2_{\gamma_{q_k}}$ was a hyperparameter with a given value. In the analysis, all of $\sigma^2_{\gamma_{q_k}}$ were specified a constant value. The hyperparameter $\sigma^2_{\gamma_{q_k}}$ was specified 1000 as a vague prior.

$\boldsymbol{\gamma_{q^{(s_{0+})}}}$:

$\gamma_{q^{(s_{0+})}} \sim N(0, \sigma^2_{\gamma_{q^{(s_{0+})}}})$, where $\sigma^2_{\gamma_{q^{(s_{0+})}}}$ was a hyperparameter with a given value. The hyperparameter $\sigma^2_{q^{(s_{0+})}}$ was specified 1000 as a vague prior.

$\boldsymbol{\eta_y}$ for $\boldsymbol{y = }$ 1988,…,2018:

$\eta_y \sim N(0, \sigma^2_{\eta_y})$, where $\sigma^2_{\eta_y}$ was a hyperparameter with a given value. In the analysis, all of $\sigma^2_{\eta_y}$ was specified a constant value. The hyperparameter $\sigma^2_{\eta_y}$ was specified 100 as a vague prior.

Final objective function

$$LL = \sum_k l_{c_k} + \sum_k (l_{s_{0+,k}} + l_{s_{1+,k}}) + \sum_k l_{B_k^{(1)}} + \log(\text{the priors of the parameters})$$

Table 31. The negative log-likelihood functions for the MATLAB spatial-M2 and non-spatial models.

-LL functions

Fishery log standardised catch rates or log survey densities, for each area:

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

where $\sigma = \max(\hat{\sigma}, \sigma_{\min})$, $\sigma_{\min}$ was the standard error from the LMM (REML) log predictions 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.

$\boldsymbol{h\ steepness}$:

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

$\boldsymbol{\theta}$:

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

$\boldsymbol{\kappa}$:

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

$\boldsymbol{harvest\ rate\ u}$:

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

Log recruitment deviations $\boldsymbol{\eta_y\ for\ y = 1988, \ldots, 2018}$:

$nssRec = 2018 - 1988$

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

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

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

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).

12.5 Supplementary information and results

Annual trends in fishing effort

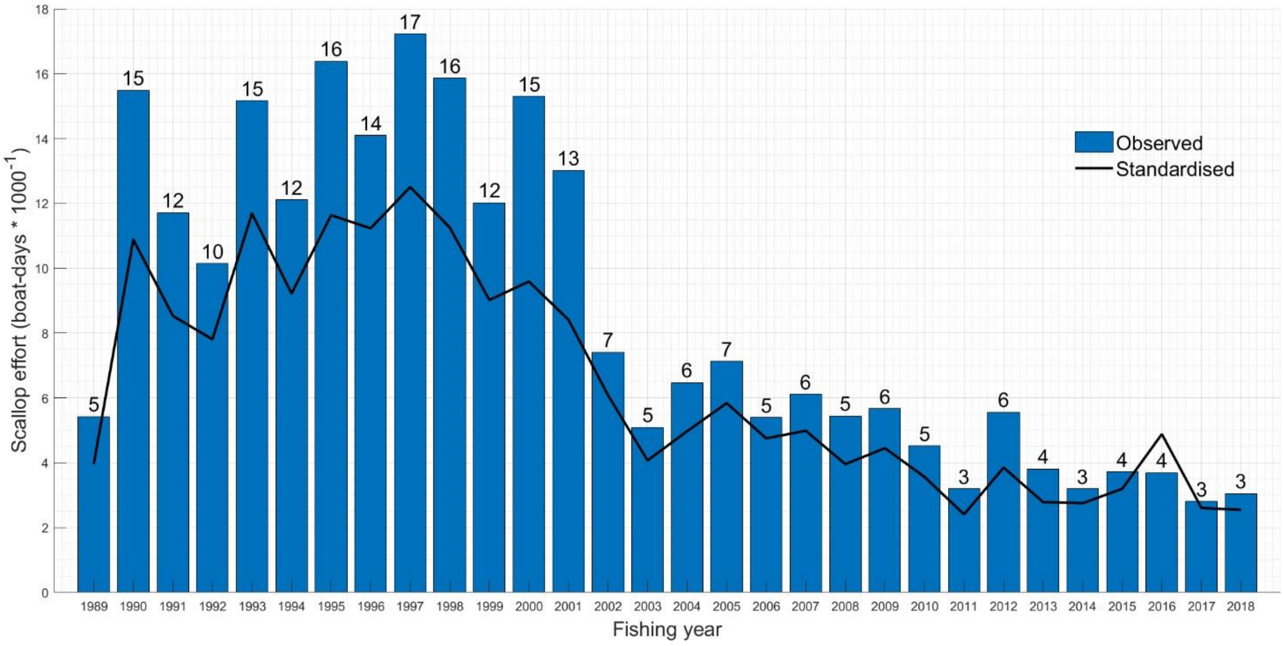


Figure 45. Annual measures of fishing effort 1989–2018. Standardised effort was from harvests divided by standardised catch rates.

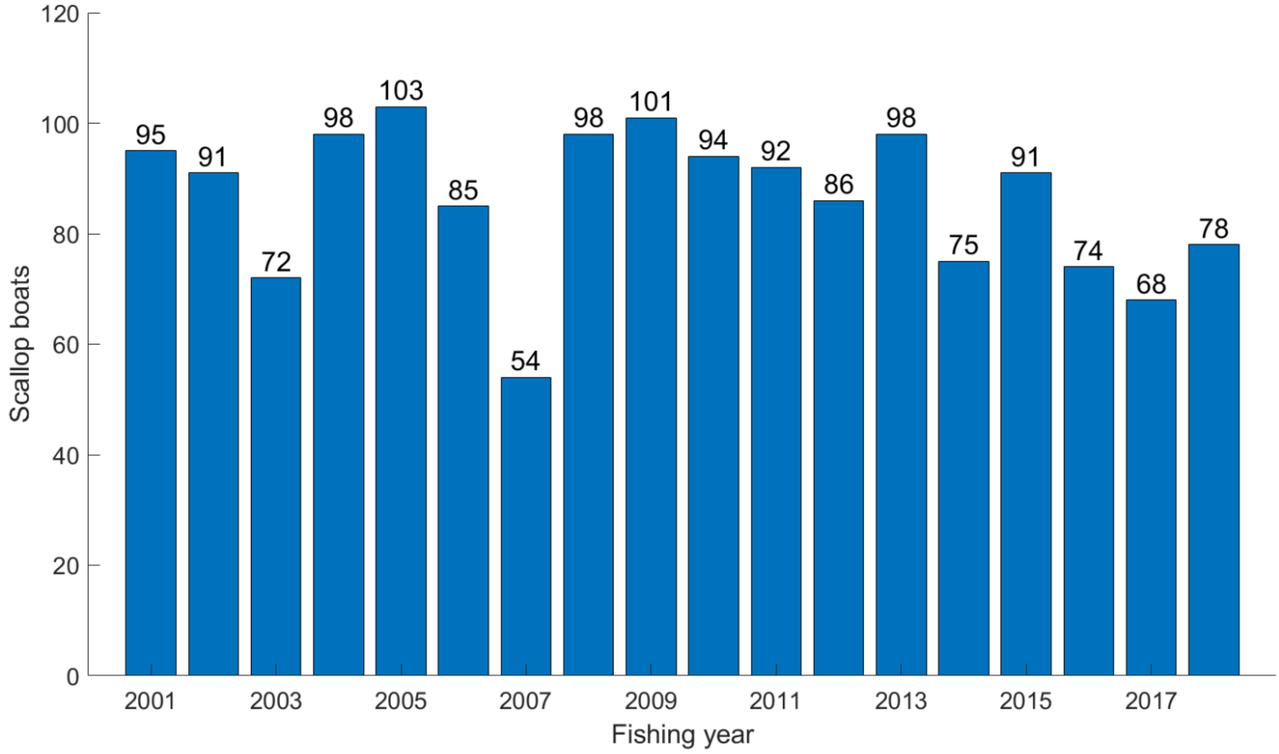


Figure 46. Annual numbers of boats harvesting scallop 2001–2018.

Standardised residual from the REML analyses

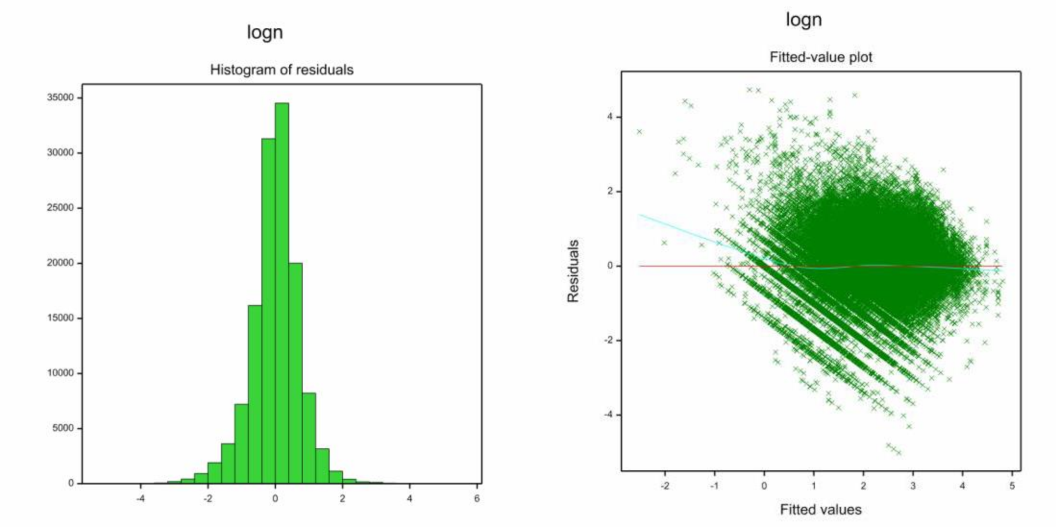


Figure 47. Standardised residuals for the scallop catch rate analysis 1988–2018, for analysis 1.

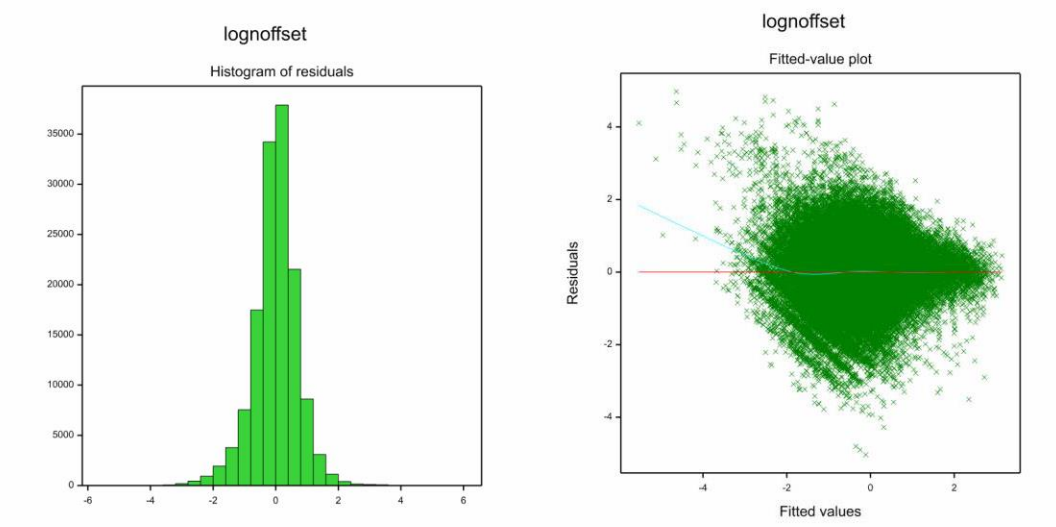


Figure 48. Standardised residuals for the scallop catch rate analysis 1977–2018, for analysis 2.

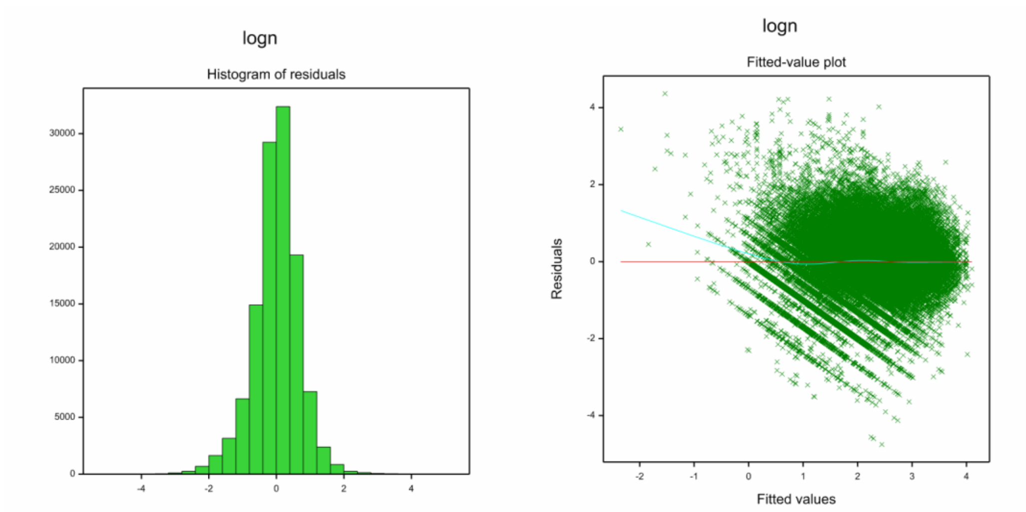


Figure 49. Standardised residuals from the scallop catch rate analysis 1988–2018, for management region 3, analysis 3.

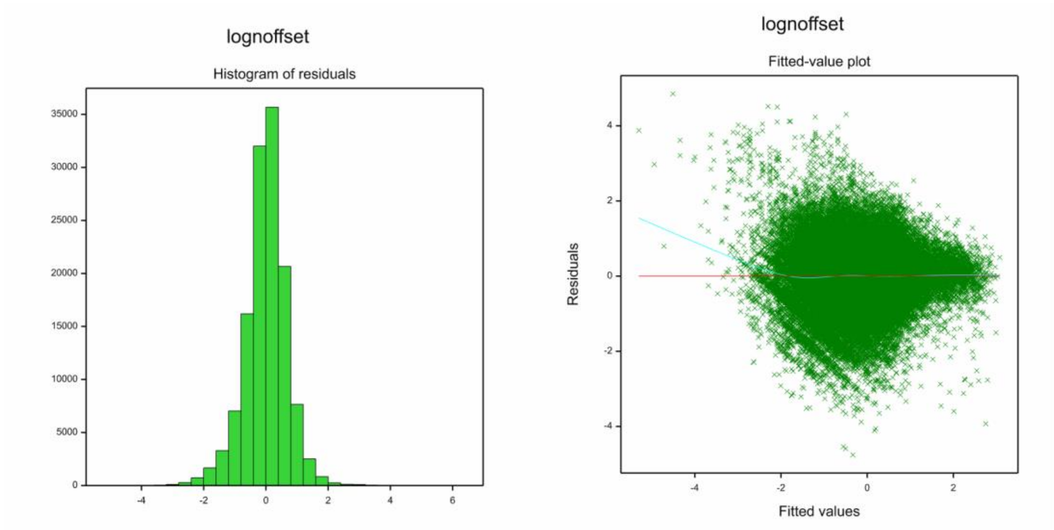
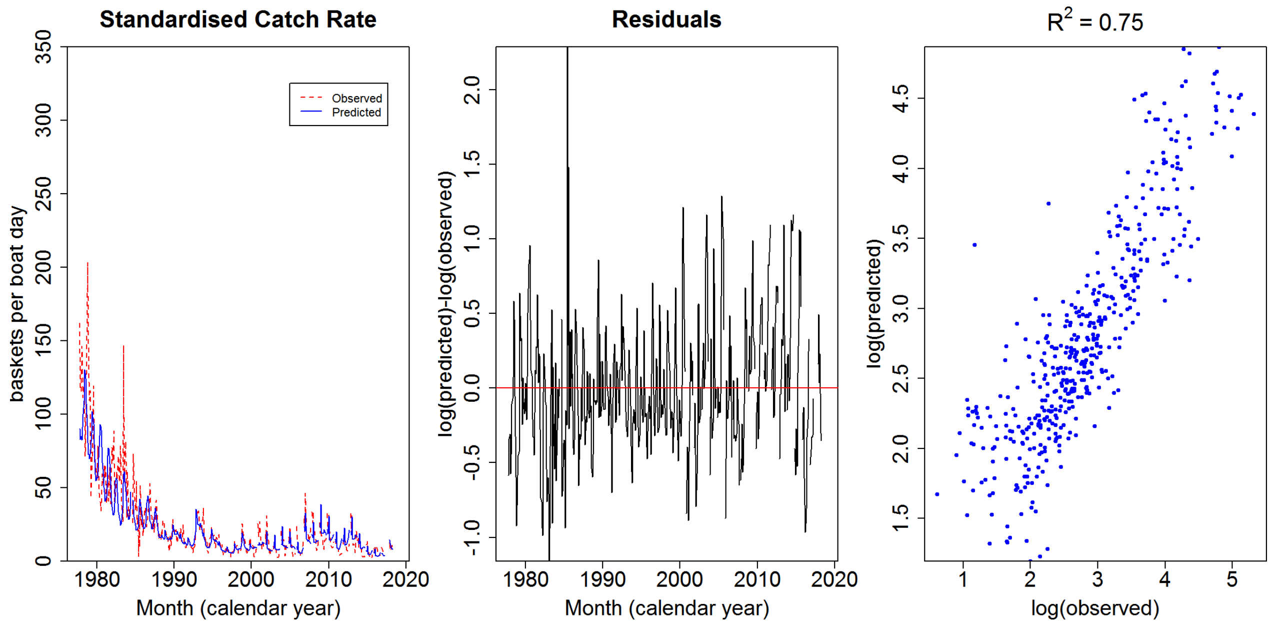


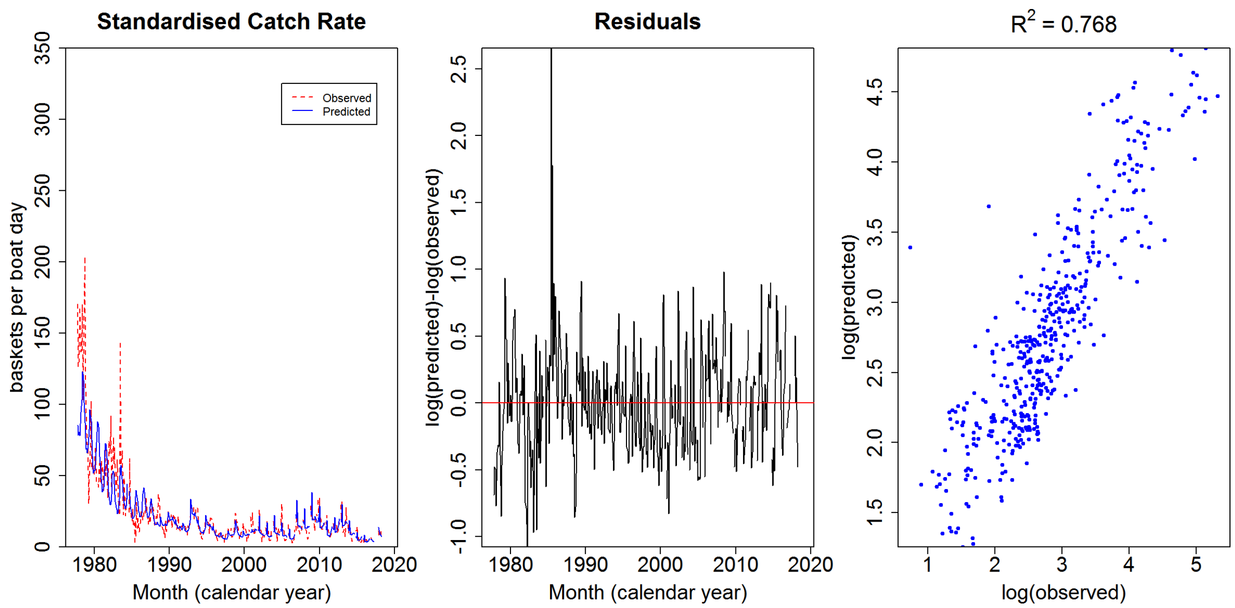
Figure 50. Standardised residuals from the scallop catch rate analysis 1977–2018, for management region 3, analysis 4.

12.6 Stock model diagnostics

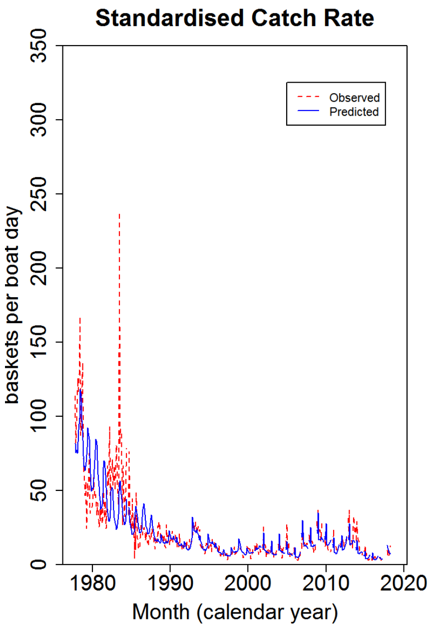
(a)



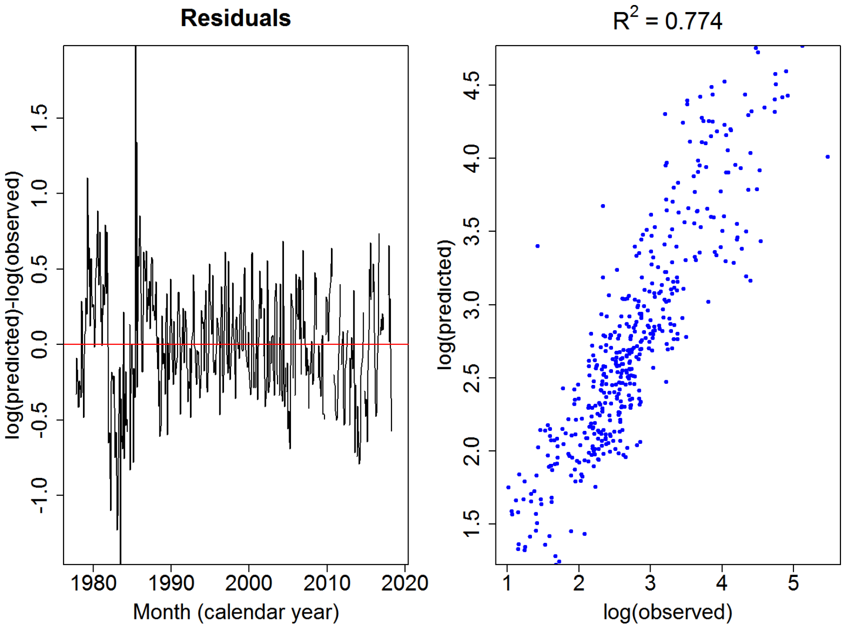
(b)



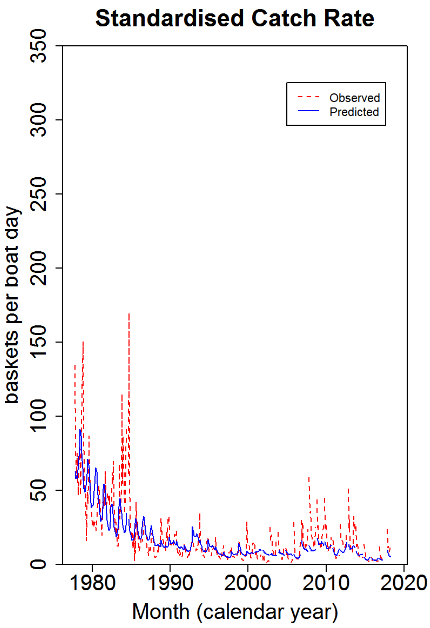
(c)



(c)



(d)



(d)

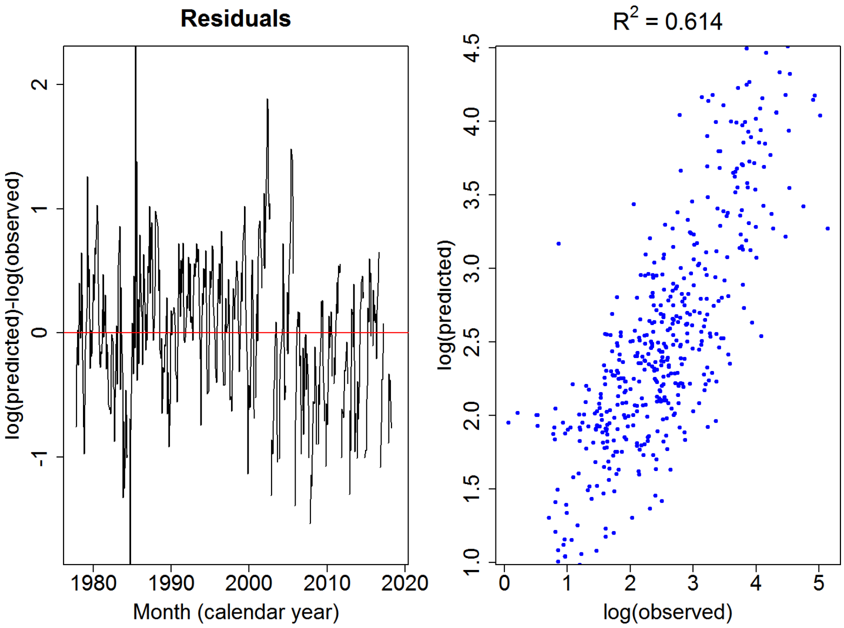
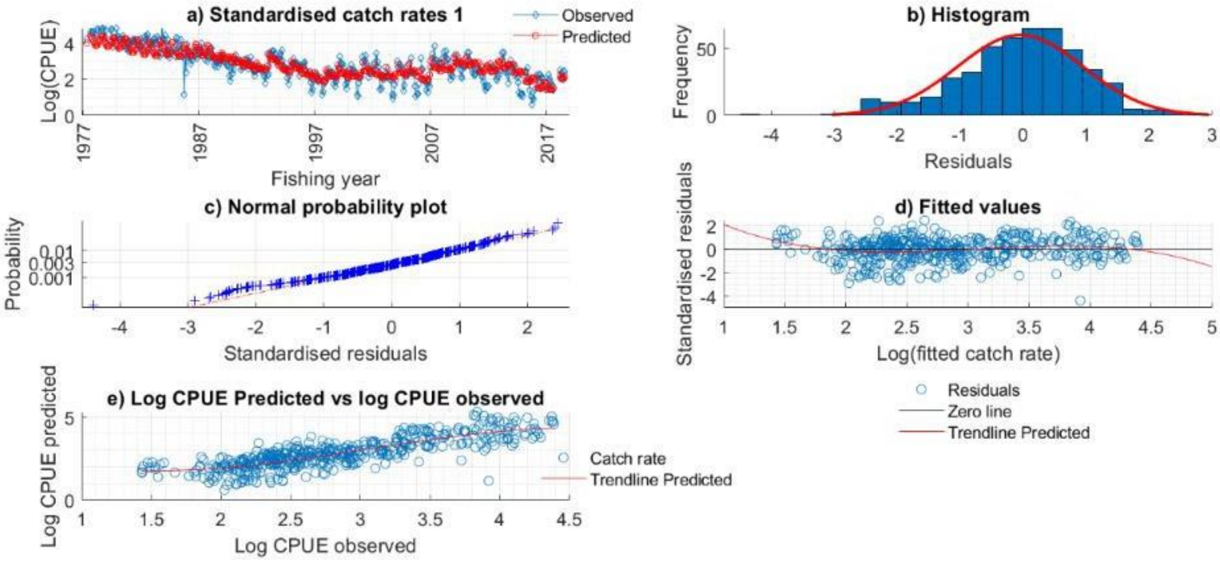
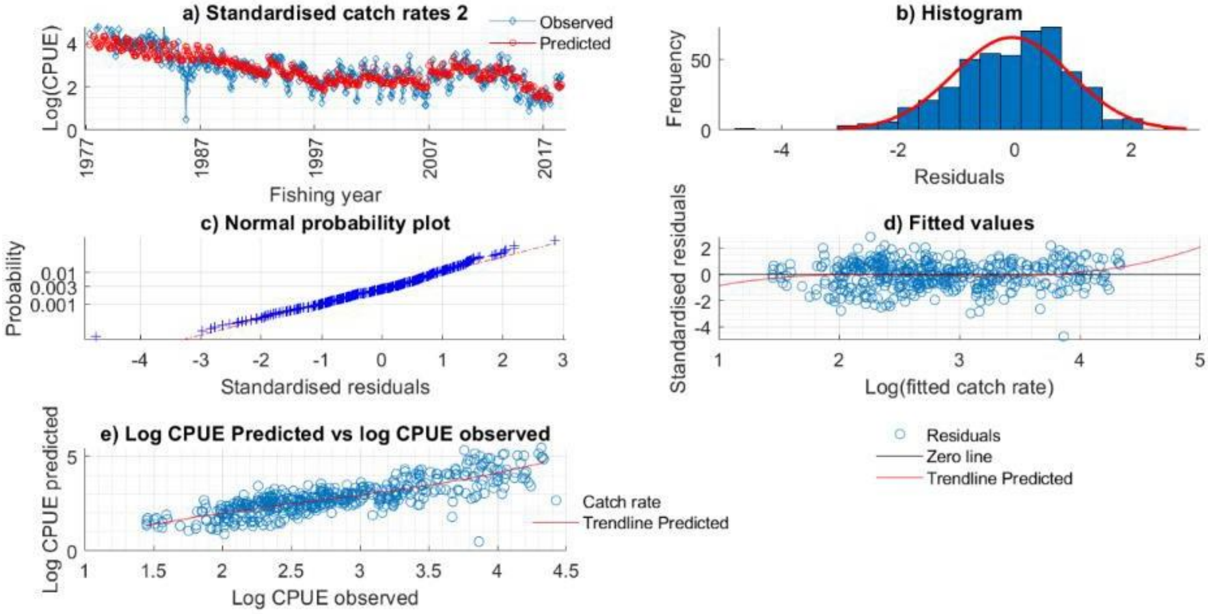


Figure 51. Catch rate fit-diagnostics for the spatial-M1 temperature-M model, using catch rates 1977–2018 and catchability of age 1+scallops=0.3. The graphs are for a) Yeppoon, b) Bustard Head, c) Hervey Bay, and d) K'gari. Catch rate predictions for survey catchabilities 0.2 and 0.4 were similar.

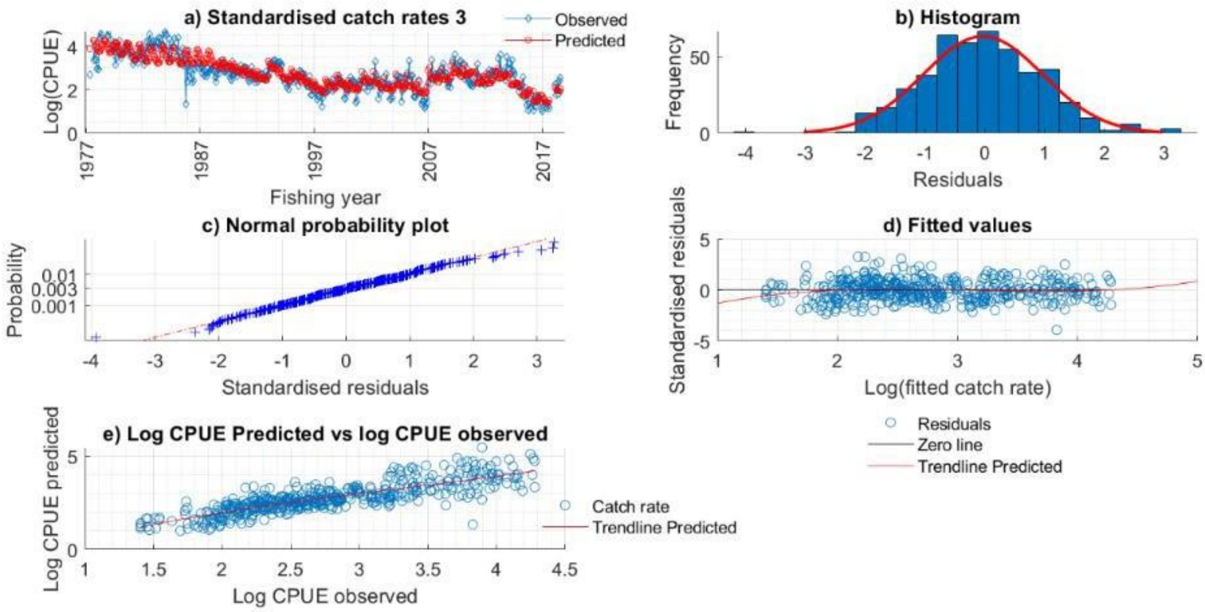
(a)


a) Standardised catch rates 1
Observed
Predicted
Log(CPUE)
Fishing year
b) Histogram
Frequency
Residuals
c) Normal probability plot
Probability
Standardised residuals
d) Fitted values
Standardised residuals
Log(fitted catch rate)
Residuals
Zero line
Trendline Predicted
e) Log CPUE Predicted vs log CPUE observed
Log CPUE predicted
Log CPUE observed
Catch rate
Trendline Predicted

(b)


a) Standardised catch rates 2
Observed
Predicted
Log(CPUE)
Fishing year
b) Histogram
Frequency
Residuals
c) Normal probability plot
Probability
Standardised residuals
d) Fitted values
Standardised residuals
Log(fitted catch rate)
Residuals
Zero line
Trendline Predicted
e) Log CPUE Predicted vs log CPUE observed
Log CPUE predicted
Log CPUE observed
Catch rate
Trendline Predicted

(c)



(d)

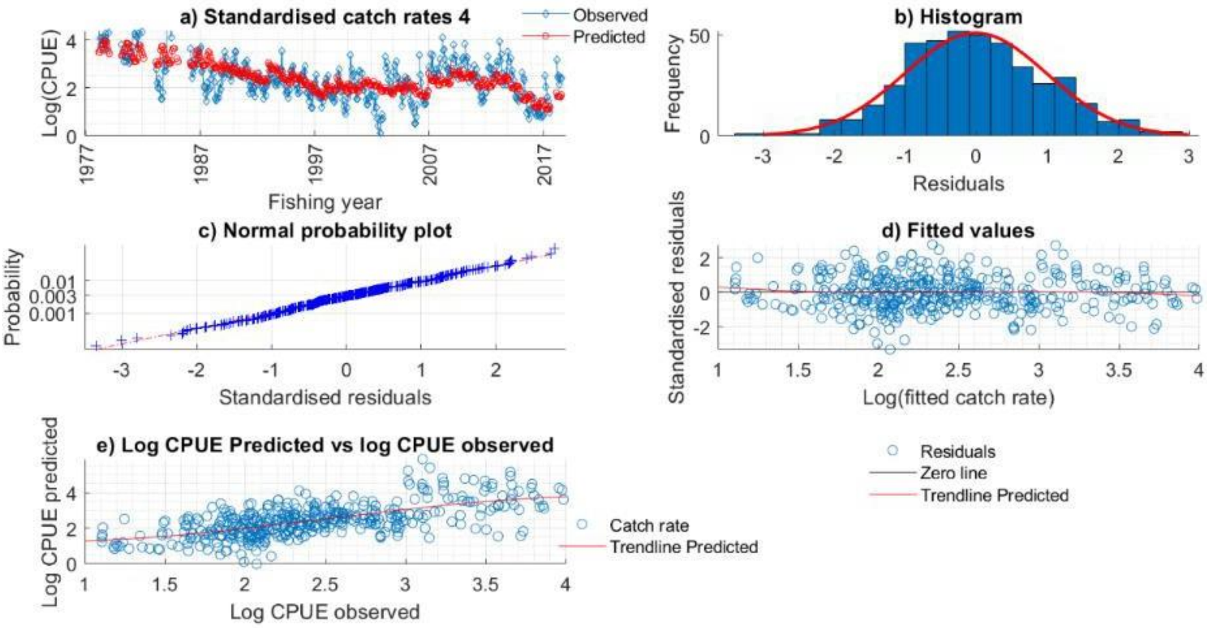


Figure 52. Catch rate fit-diagnostics for the spatial-M2 temperature-M model, using catch rates 1977–2018 and catchability of age 1+scallops=0.3. The graphs are for a) Yeppoon, b) Bustard Head, c) Hervey Bay, and d) K'gari. Catch rate predictions for survey catchabilities 0.2 and 0.4 were similar.

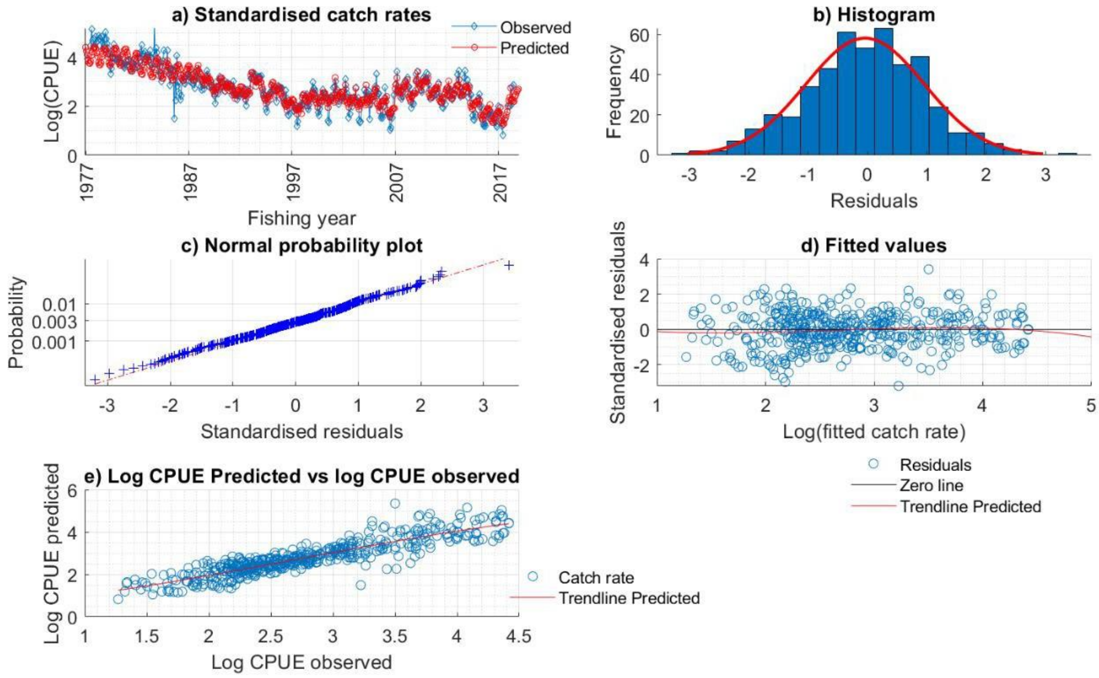


Figure 53. Catch rate fit-diagnostics for the non-spatial and non-temperature-M model, using catch rates 1977–2018 and catchability of age 1+scallops=0.3. The result was for proposed management region 3.

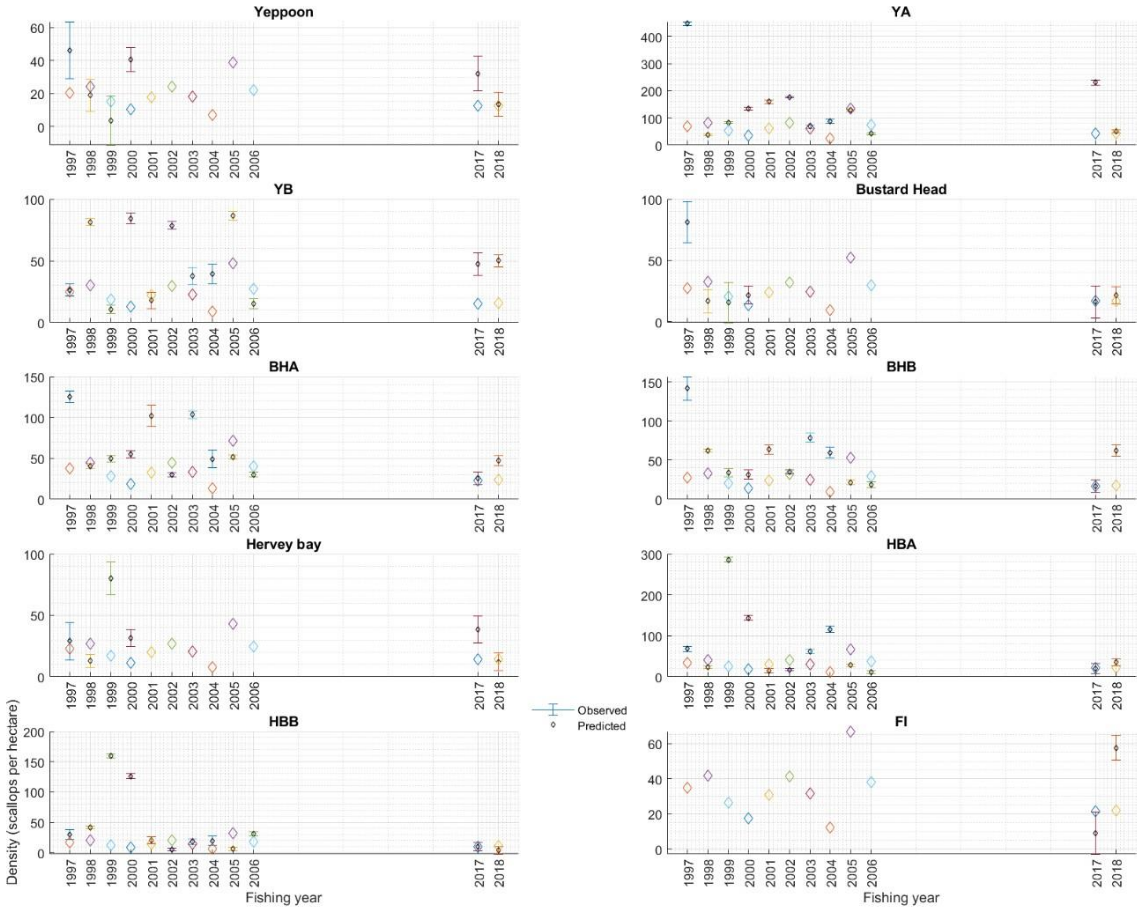


Figure 54. Relative 0+ densities from the spatial-M1 model and catch rates 1977–2018. Error bars were ± one standard error.

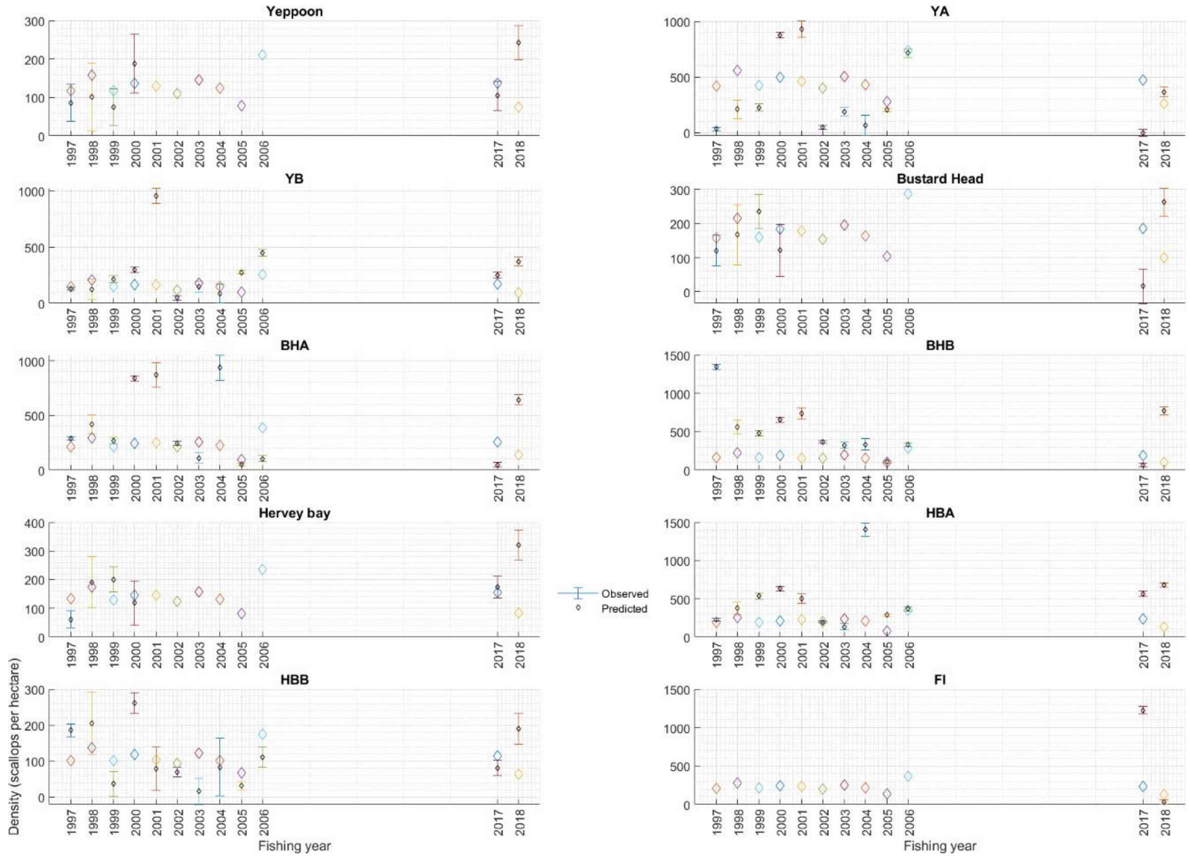


Figure 55. Absolute 1+ densities from the spatial-M1 model for catch efficiency of age 1+ scallops q1+=0.3 and catch rates 1977–2018. Error bars were ± one standard error.

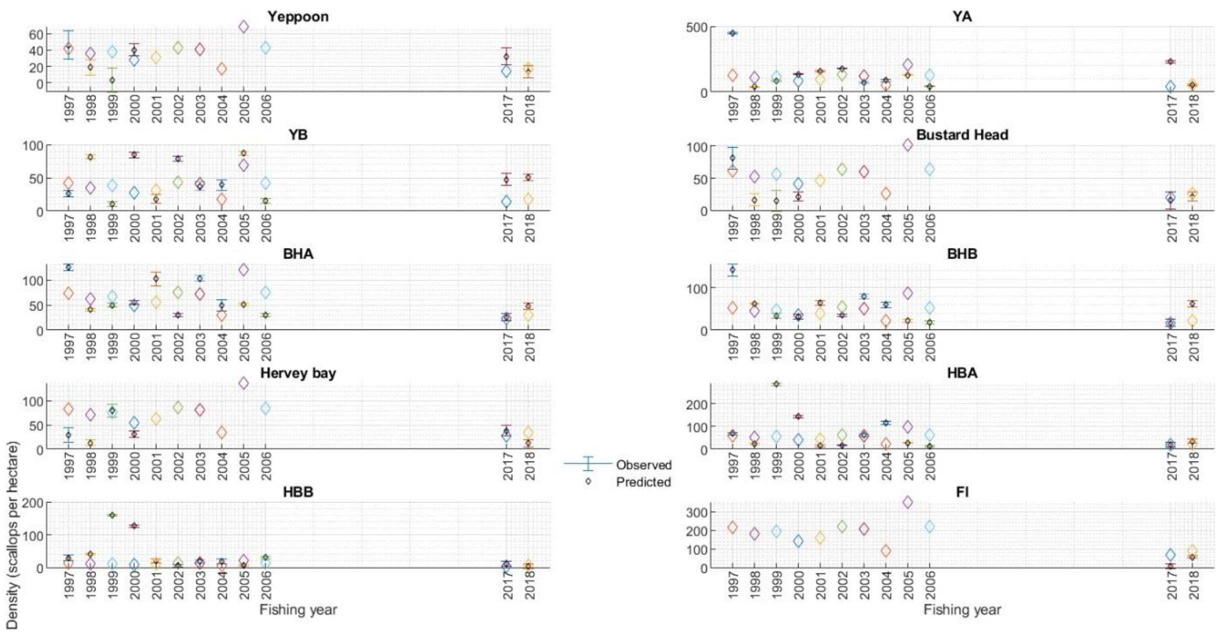


Figure 56. Relative 0+ densities from the spatial-M2 model, for catch rates 1977–2018. Error bars were ± one standard error.

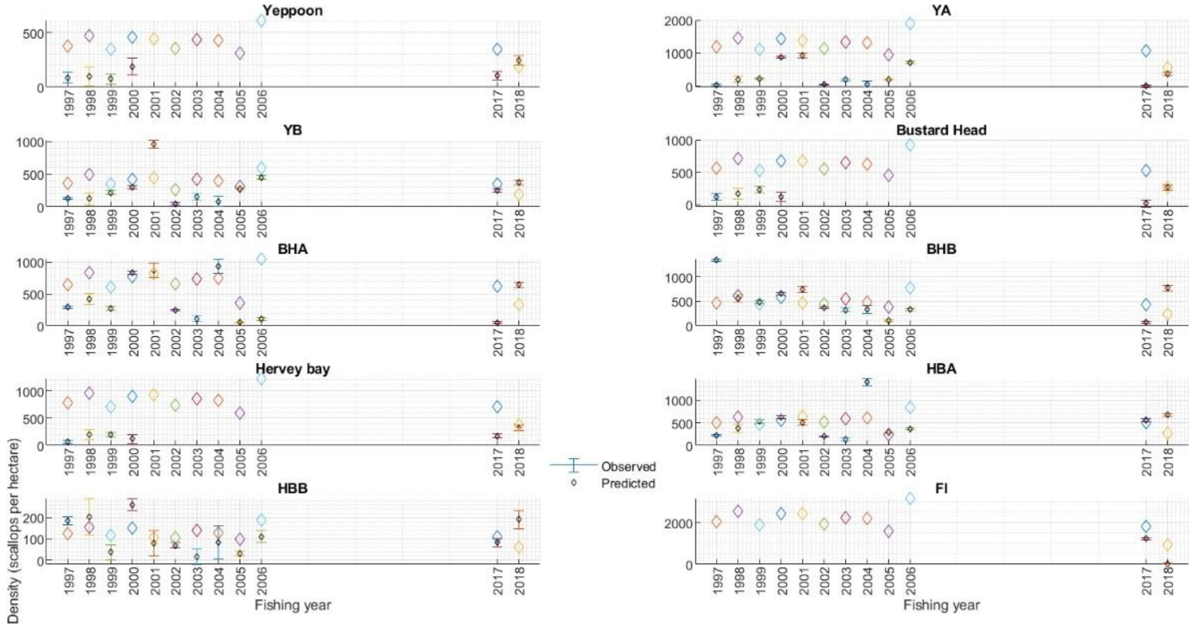


Figure 57. Absolute 1+ densities from the spatial-M2 model for catch efficiency of age 1+ scallops q1+=0.3 and catch rates 1977–2018. Error bars were ± one standard error.

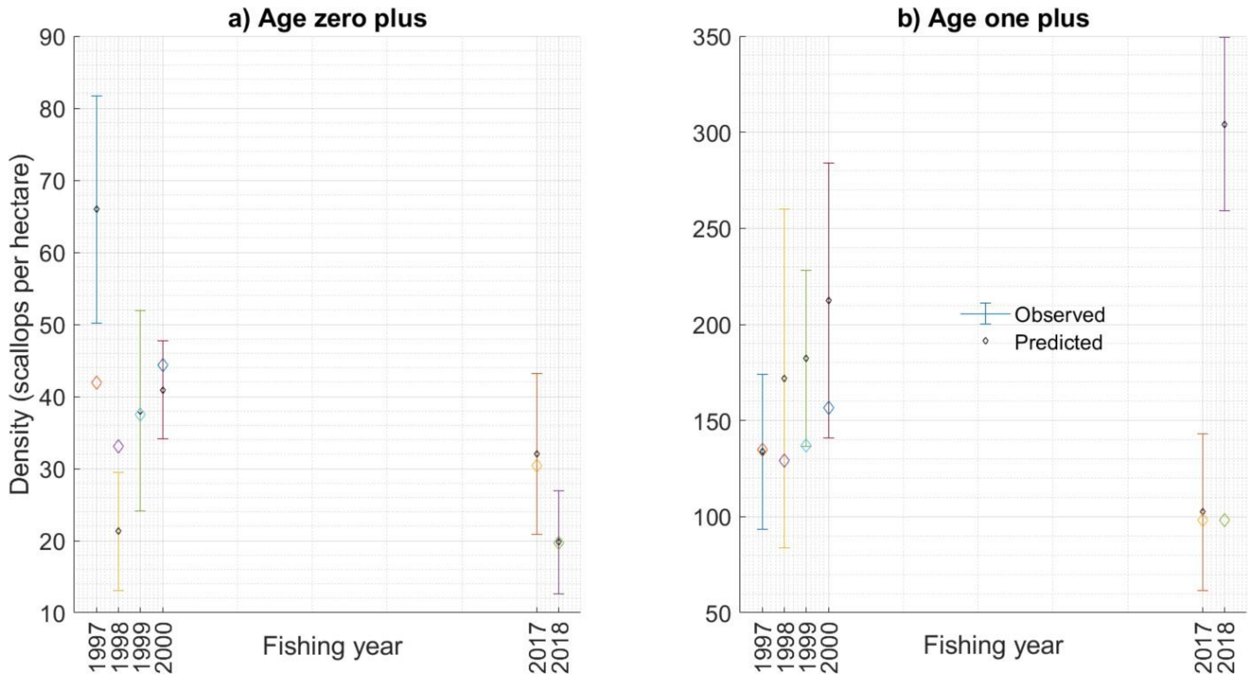


Figure 58. 0+ and 1+ densities from the non-spatial model for catch efficiency of q1+=0.3 and catch rates 1977–2018. The error bars depict ± one standard error.

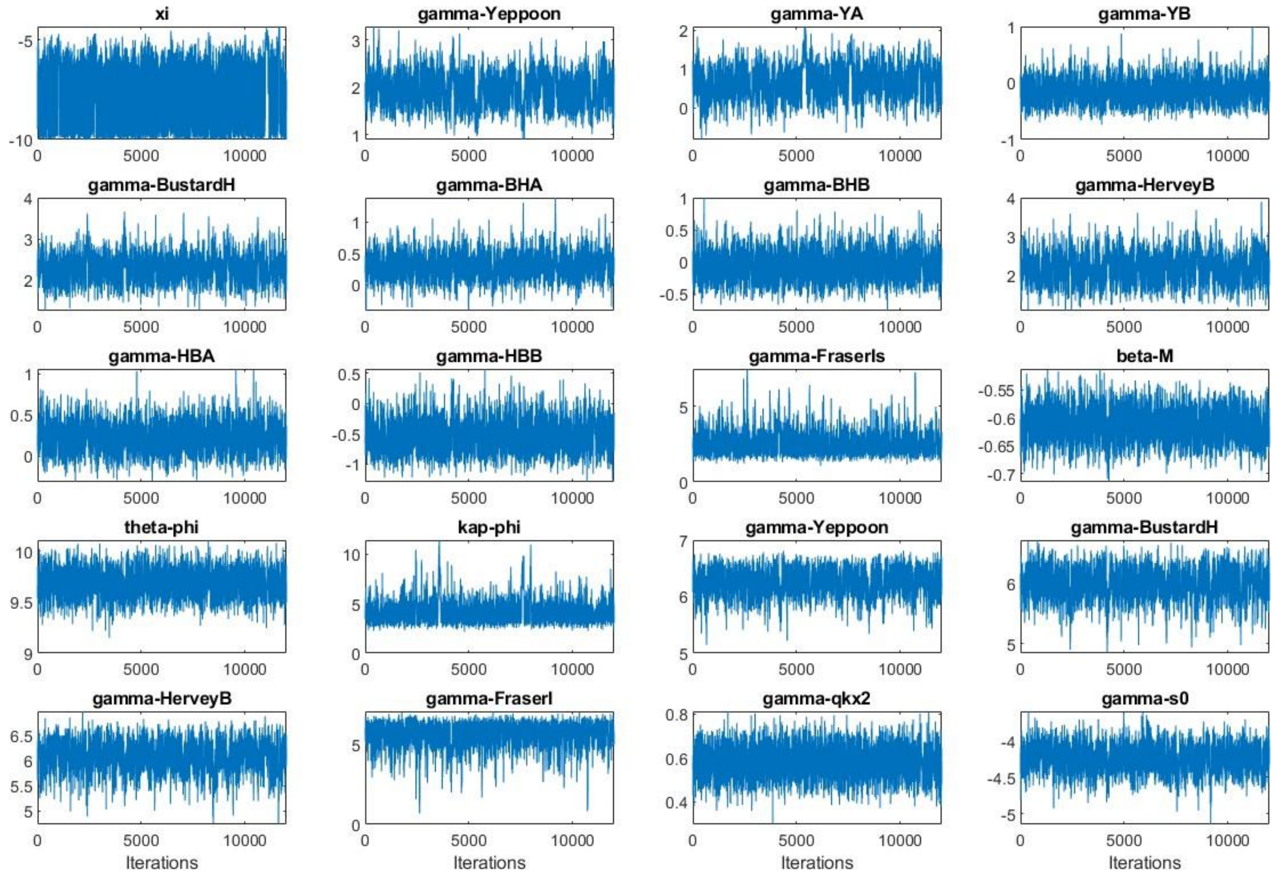


Figure 59. Example MCMC traces for key parameters in spatial-M1 model with SST. n = 12 000, using a thinning rate of 200. Some parameters were highly correlated.

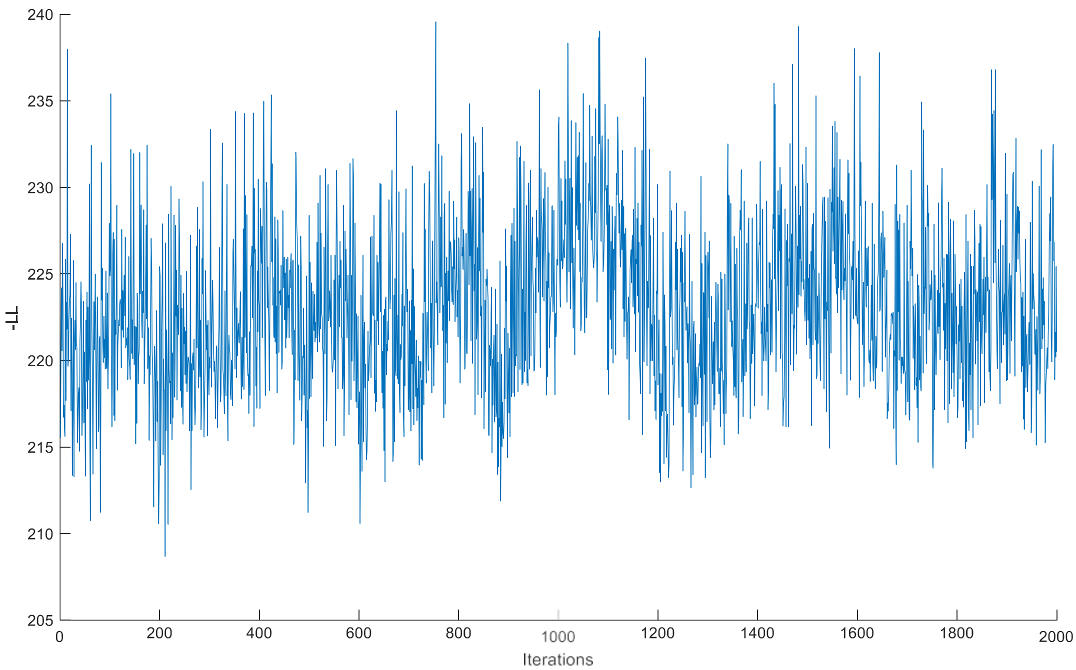


Figure 60. MCMC –LL trace for the non-spatial model with no SST. n = 2000 samples, thinned from 200 000 iterations of each parameter.

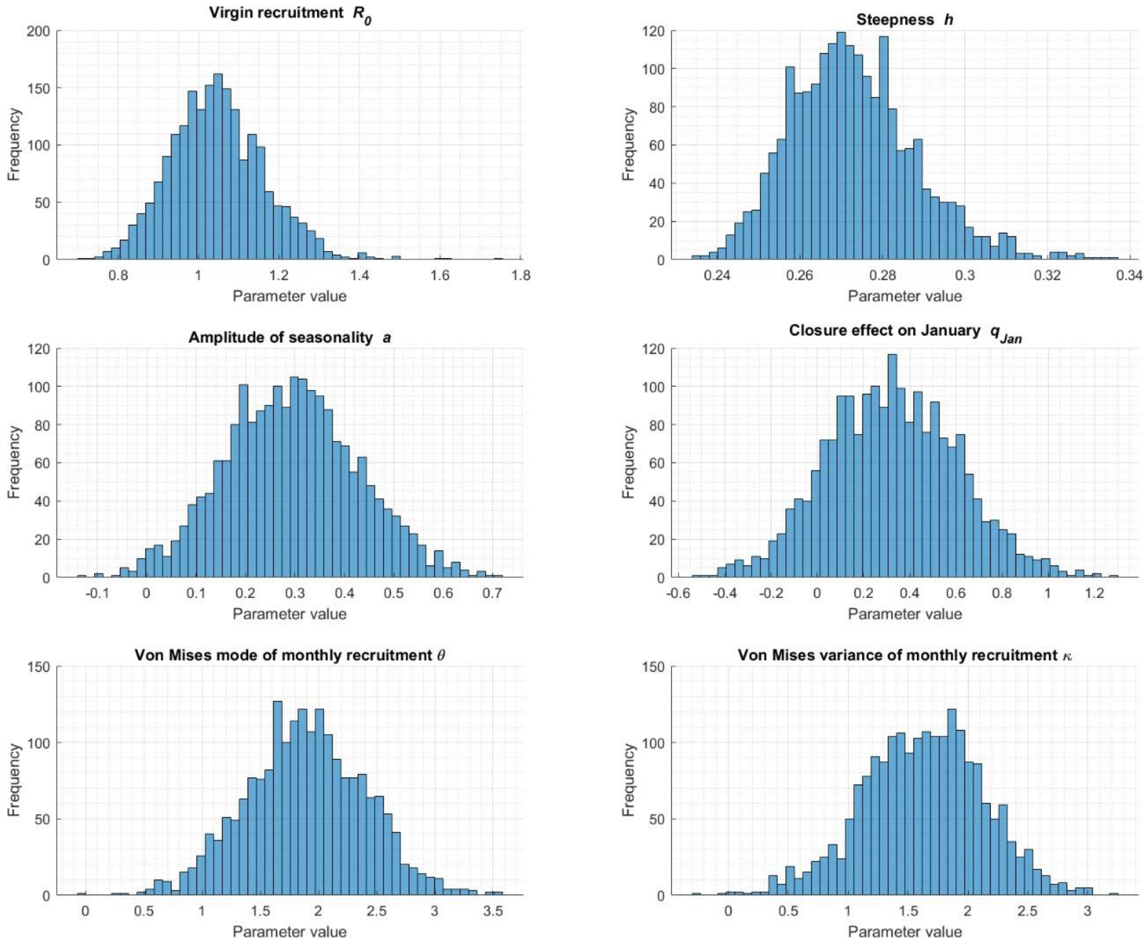


Figure 61. MCMC parameter estimates for the six main parameters from the non-spatial model for zone 3, with no SST. n = 2000 samples, thinned from 200 000 iterations of each parameter.

12.7 Vessel configurations and fishing power

Vessels

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 previous 2016 stock assessment (Yang et al., 2016). The vessel trends were:

- The average engine horsepower increased by about 100 HP between 1990 and 2018 (Figure 62).
- Average trawling speeds were faster at about 2.7 knots in 2018, compared with 2.3 knots in 1988 (Figure 62).
- The proportion of vessels with a propeller nozzle was near 100% in 2018 (Figure 62).
- Net sizes (head rope length) were generally the same (Figure 62).
- Since 2007, there was a trend for more vessels to tow quad gear than triple gear. By 2018, about 80% of total fishing effort used quad gear. Few vessels towed twin or five nets. See Figure 63.
- Standard drop chains and their variants were the most commonly used ground gear (Figure 64).
- The use of flat otter boards declined between 1988 and 2018, and there was an increase in the adoption of Louvre and Kilfoil otter boards. By 2018, about 60% of total fishing effort was by vessels using Louvre and Kilfoil otter boards. See Figure 65.

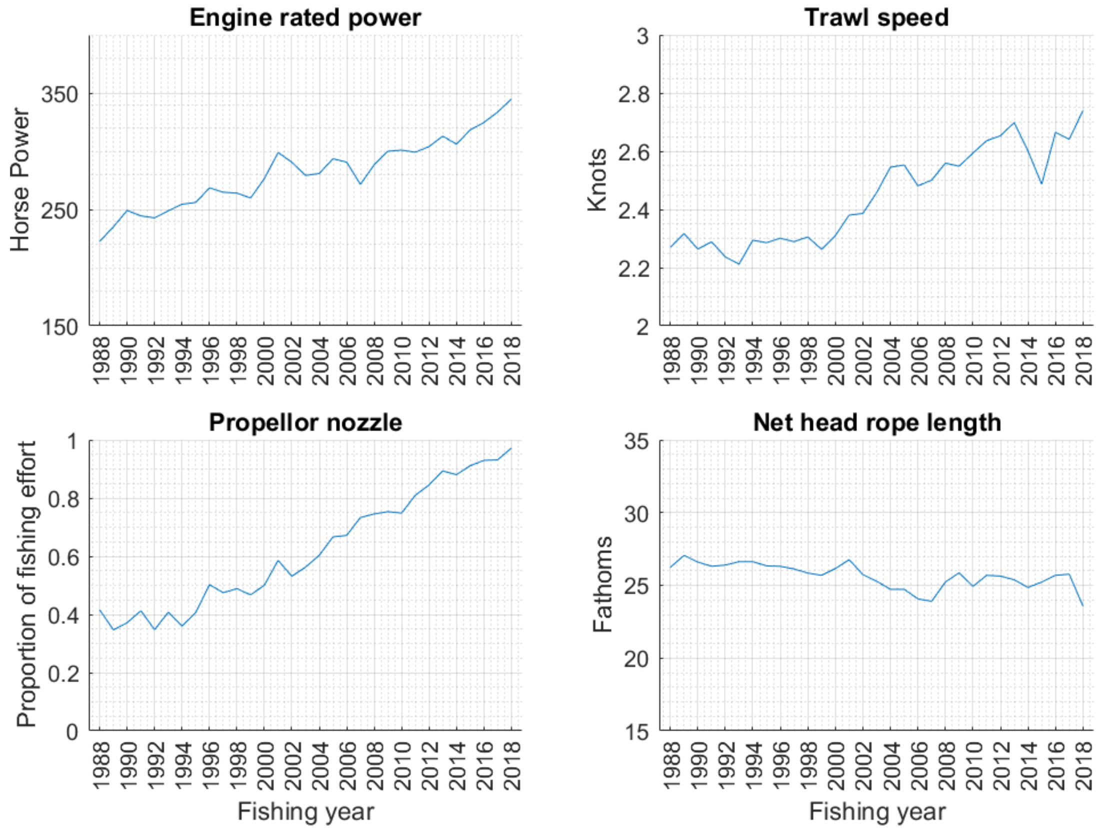


Figure 62. The scallop-fleet average engine rated power, trawling speed, use of propeller nozzles and net size by fishing year. Averages weighted according to the number of days fished by each vessel in each fishing year.

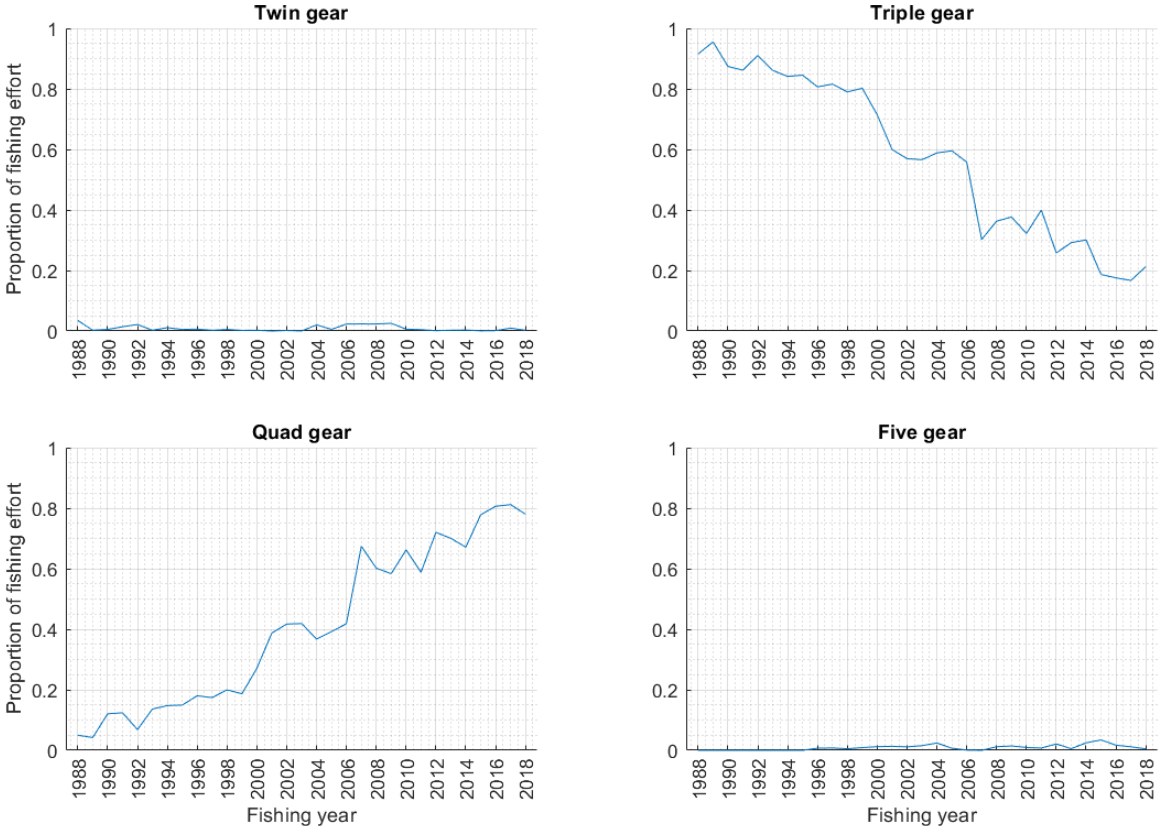


Figure 63. The proportion of total annual fishing effort by vessels using the net configuration.

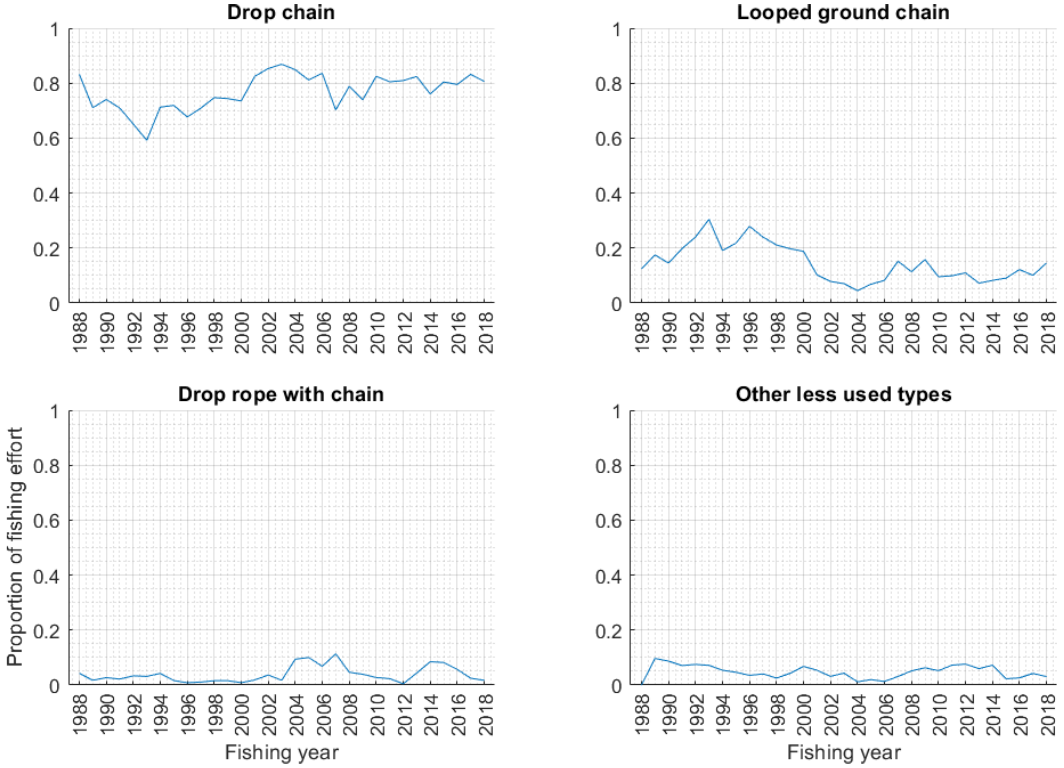


Figure 64. The proportion of total annual fishing effort by vessels using the ground gear configuration.

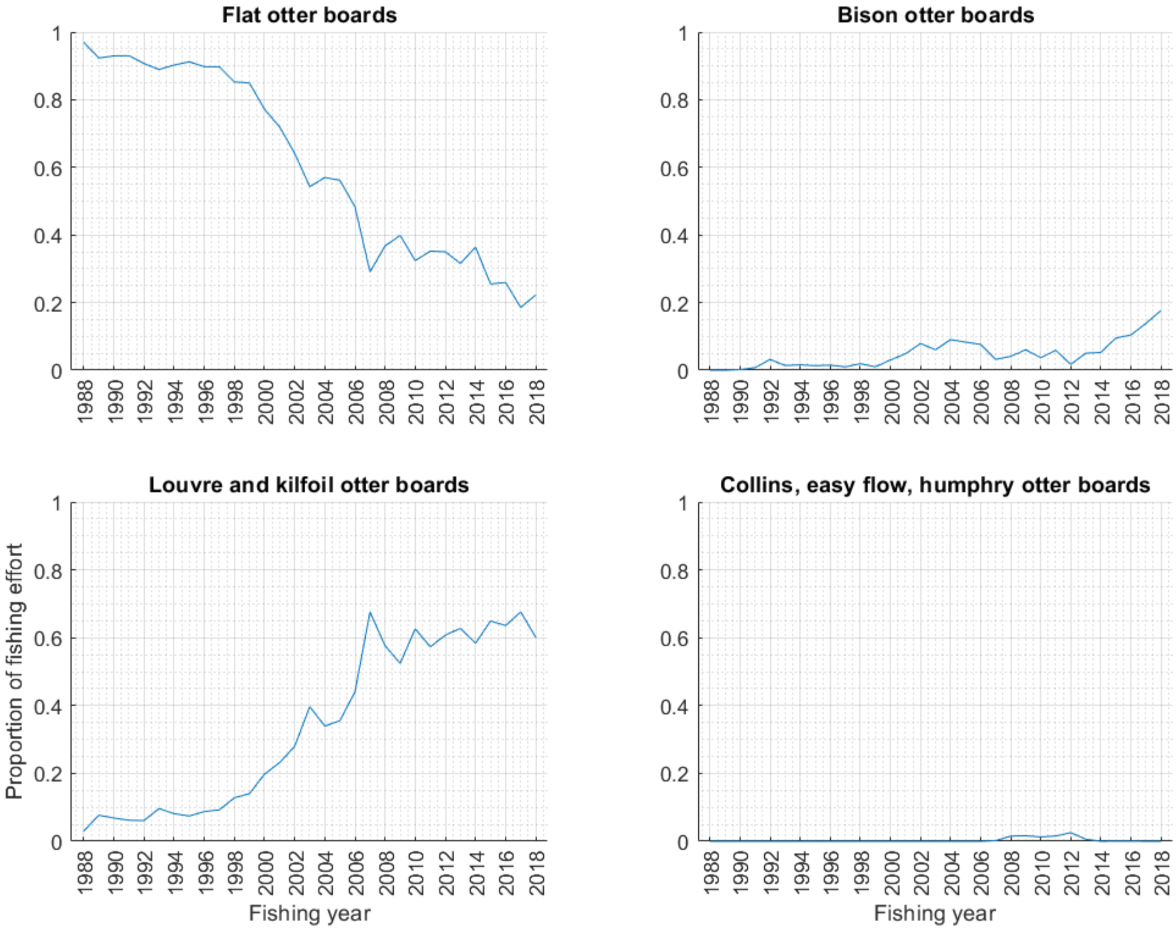


Figure 65. The proportion of total annual fishing effort by vessels using the otter board configuration.

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 66, where fishing power increased by about 20% from 1989–2018. 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 fixed and random (vessel) terms, showed that fishing power increased by about 26% from 1989–2018.

Parameter estimates β_2 and standard errors in parentheses from the mixed linear model are in Table 32.

The median hours fished per boat-day increased from around 10.3 hours in 1992 to around 12 hours per day from 2000 onwards (Figure 67).

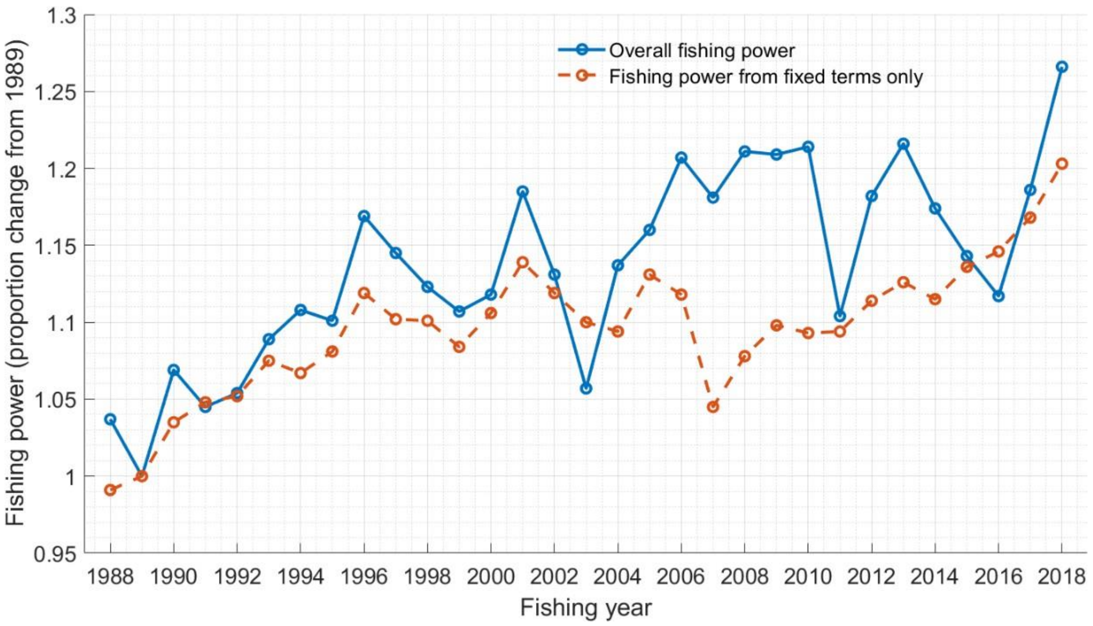


Figure 66. Annual fleet fishing power on saucer scallops, as calculated from the REML model. The changes represent the difference from year 1989, which was set at one.

Table 32. Parameter estimates and standard errors for the linear mixed model fitted to catch rates 1988–2018. Ground gear 1–4 represent drop chain, looped ground chain, drop rope with chain and other less used types. Net types 2–5 represent twin, triple, quad and five gear. Twin nets (i.e. nettype 2) and drop chain (i.e. ggear 1) were the default reference net type and ground gear, respectively.

Parameter	Estimate	Standard error
loghours	0.7123	0.00605
loghp	0.3887	0.02008
sonar	0.1849	0.01107
gps2	0.0457	0.012472
nettype 2	0	0
nettype 3	0.2994	0.0355
nettype 4	0.2323	0.0362
nettype 5	0.2666	0.0589
ggear 1	0	0
ggear 3	0.04836	0.00978
ggear 4	-0.06059	0.01469
ggear 5	-0.27314	0.01664

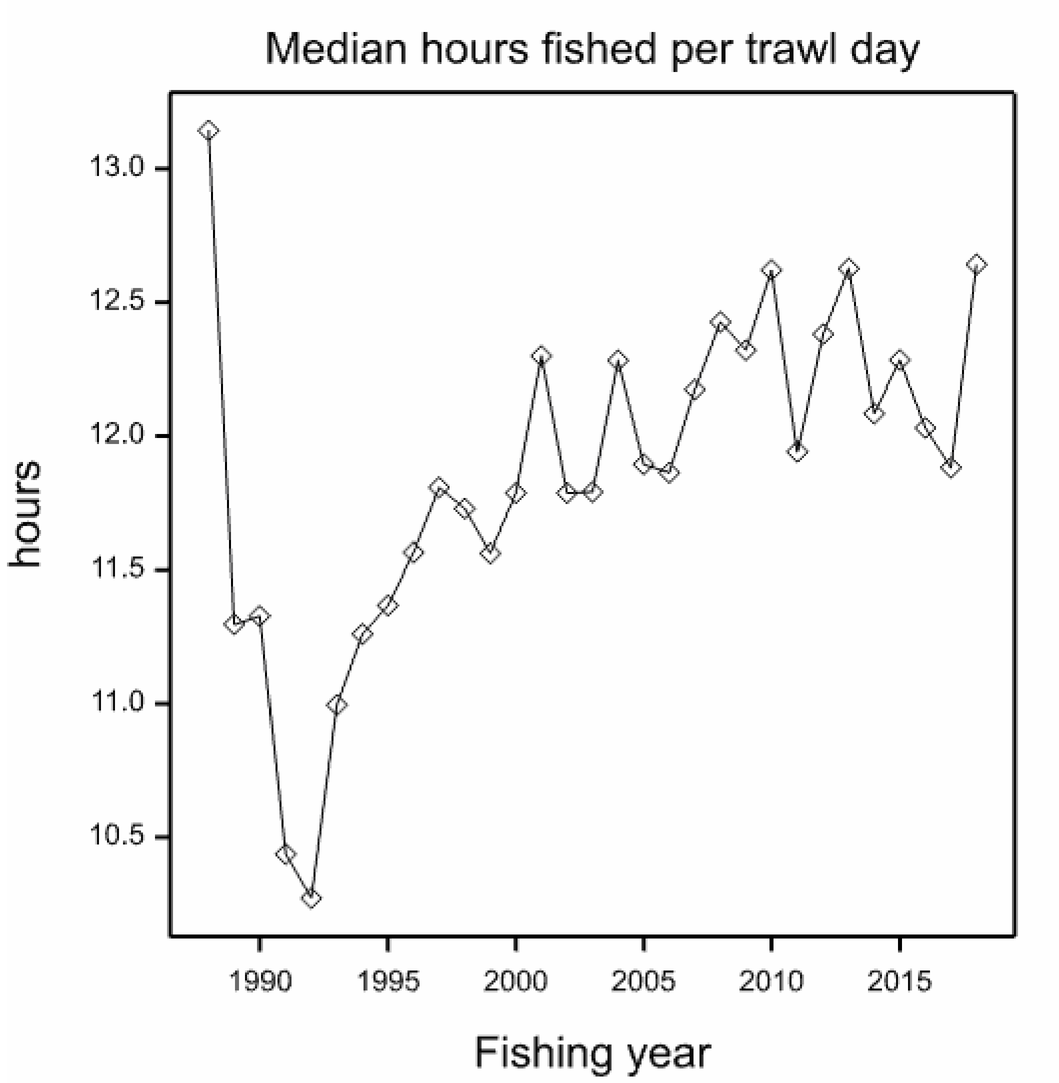


Figure 67. Median hours fished per boat-day, from the linear mixed model data.

12.8 List of researchers and project staff

Dr Michael O'Neill, Principal Fisheries Scientist, Department of Agriculture and Fisheries, Queensland.

Dr Wen-Hsi Yang, Research Fellow, CARM, The University of Queensland.

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Dr Tony Courtney, Senior Principal Fisheries Scientist, Department of Agriculture and Fisheries, Queensland.

Mr Matthew Campbell, Senior Fisheries Scientist, Department of Agriculture and Fisheries, Queensland.

Dr George Leigh, Principal Fisheries Scientist, Department of Agriculture and Fisheries, Queensland.

Prof Jerzy Filar, Director, CARM, The University of Queensland.

12.9 Intellectual property

The project produced no marketable intellectual property.