Department of Agriculture and Fisheries

Quantitative assessment of the Queensland saucer scallop (*Amusium balloti*) fishery, 2016

November, 2016

Queensland Government

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Summary

In recent years (i.e. 2015–2016) there has been growing concern from members of the fishing industry and the Queensland Government over declining catches of legal-sized saucer scallop, particularly from areas that have traditionally sustained profitable fishing. This led to a request in mid-2016 by Fisheries Queensland, the fisheries management service within the Department of Agriculture and Fisheries, for an investigative analysis on the declined status of saucer scallops. The scope of the investigation was limited to a short time frame of three months to analyse the most recent and comprehensive data and undertake a stock assessment. This report provides findings that support the concerns of low abundance of legal-sized scallops.

Two time series of standardised catch rates (i.e. monthly mean number of baskets of whole scallops harvested per standardised boat-day) were estimated for an index of legal-sized scallop abundance. Both time series were derived from linear mixed models (the statistical estimation used restricted maximum likelihood: REML). The first time series covered the period from 1977–2016 and included both the 'voluntary historical data' (also known as HTRAWL) from 1977–1987 and the mandatory CFISH logbook data from 1988–2016. The second shorter time series was based solely on the 1988–2016 CFISH data.

The catch rate times series were standardised (adjusted) for changes in fishing power through time due to shifts in the fleet's vessel-profile (e.g. changing number of higher verse lower catching vessels) and variation in gear technologies (e.g. engine sizes, net types, and the use of global positioning systems). The REML models estimated that trawler fishing power (the fleet's average catching ability for scallops) increased by about 43% from 1977–2016 and about 15% from 1989–2016.

The long-term trend in standardised catch rates of scallops from 1977–2016 declined markedly after 1986. From 1977–1979, catch rates generally exceeded 100 baskets per boat-day. From 1980–1984, catch rates averaged about 50 baskets per boat-day. In recent months, from January 2015 to April 2016, standardised catch rates averaged 5 baskets per boat-day. To put this in management context, in 1996 when the scallop population was considered to have collapsed and emergency closed areas were implemented by the Government, scallop catch rates averaged 8 baskets per boat-day. Standardised catch rates from January 2015 to April 2016 are the lowest in the 39-year record of catch rates.

Fishing regulations in the scallop fishery from 1977–1987 were generally less conservative compared to the post-1988 years and may explain the long-term changes in catch rates to some degree, but they are less likely to explain changes after 1989. The key influence of extended daily hours of fishing on catch rates pre-1988 was standardised through REML and adjustments for changes in the minimum legal sizes (MLS) of scallops were performed through the stock model.

From the catch rate signals, spawning trends were predicted using the monthly-age-structured stock model by Campbell *et al.* (2012). The model integrated information on scallop total harvests, standardised catch rates, spatial fishing effort, size selectivity, past survey estimates of scallop abundance and other important biological and management data. The stock model synthesised two predictions: 1) when the long term catch rates were used the 2015 spawning stock ratio was estimated to have crashed to about 5-10% of 1977 levels, and 2) when the shorter term catch rates (omitting 1977–1987 HTRAWL data) were used the 2015 ratio estimates were between 20-50% of 1977 levels. Statistical confidence in model predictions fell when the longer term catch rate information was omitted. The most reliable model estimates indicate that the spawning stock ratios are potentially as low as 5-6% of 1977 levels. The results should be interpreted cautiously and further modelling and hypotheses need to be tested.

Given the following results from the analyses: a) record-low catch rates from January 2015 to April 2016, b) extremely low annual landings in 2014 and 2015, and c) an extremely low estimate of spawning stock, we conclude the likely current status of the saucer scallop fishery to be recruitment overfished. The most pessimistic results place the stock in a seriously depleted condition and if they were interpreted under the Australian Government (2007) fishery control rules, then closure of the fishery would be justified.

Based on the findings, new management measures are urgently required to significantly reduce fishing effort in order to allow the population of legal-sized scallop to rebuild. Minor changes to effort, catch or minimum legal sizes will be insufficient and are not recommended. The new management measures will need to consider different procedures that assume a precautionary stock-size estimate and appropriate limits to the number of vessels and effort.

Annual scientific surveys of scallop abundance would be of benefit to validate stock status, track recovery and inform future management arrangements; but awaiting this information should not be a reason to delay management action.

A formal harvest strategy, consistent with the reforms proposed in the recent Green Paper on fisheries management reform in Queensland, would be of benefit, including clear limit and target reference points and harvest control rules.

Recent research has demonstrated some associations between scallop standardised catch rates and freshwater flow, chlorophyll-a, water temperature and properties of the Capricorn Eddy which is located adjacent to the scallop fishery. However, additional time and resources are required to examine these relationships further and their meaning for management.

The current low stock status and poor economic performance in the scallop fishery are likely to have a serious impact on some vessel operators and seafood processors. Logbook data indicate that the average annual gross value of scallops from the fishery has declined from about AUD$16 million in the early 1990's to about AUD$4 million in 2014–2015 fishing years (i.e. 75% decline in value, based on 2012 price data). The low levels of fishing effort applied in recent months are sustained by the retention of byproduct species, particularly Moreton Bay bugs, which now account for most of the scallop fishery's catch value.

Finally, several recommendations for improving future assessment of the scallop stock are provided. These include:

1. incorporating key environmental influences in the population dynamics
2. improved access to the raw LTMP fishery-independent survey data (1997–2006)
3. where possible, improve the allocation of weighting to dataset components in the log likelihood function
4. incorporating additional spatial influences in the population model
5. further checking and validation of the HTRAWL and CFISH logbook data.

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Abbreviations/Acronyms

ADMB	Automatic Differentiation Model Builder
BRD	bycatch reduction device
BRN	boat record number
CPUE	catch per unit effort or catch rate
FRDC	Fisheries Research and Development Corporation
GPS	global positioning system
HP	engine horse power
LTMP	long-term monitoring program
MSY	maximum sustainable yield
REML	restricted maximum likelihood (type of linear mixed model)
TED	turtle excluder device (TEDs are one type of BRD)
VMS	vessel monitoring system

Herein standardised catch rates are defined as the average catch rates adjusted/scaled to a constant vessel and fishing power through time.

1 Background and Need

In recent years (i.e. 2015–2016), there has been growing concern among fishers, seafood processors, Fisheries Queensland managers and scientists over the decline in catch rates, annual harvest and fishing effort in the Queensland saucer scallop (*Amusium balloti*) trawl sector. In late 2015, the situation prompted a group of fishers to put forward a range of alternative management measures for the fishery, including a winter closure. Fisheries Queensland discussed the proposal with a large number of scallop fishers. However, no course of action could be agreed upon and no changes to the current management regime were implemented.

The concerns are supported by recent logbook data analyses that were undertaken as part of the ‘Status of Key Australian Fish Stocks Reports 2016’ (in press). The declining fishing effort is also reflected in satellite polling data obtained from the fishery’s Vessel Monitoring System (VMS). The logbook analyses confirm that catch rates, annual landings and fishing effort have declined markedly since 2013. The trends are consistent with a significant decline in the population of legal-sized scallops throughout the fished area. Ongoing concern in 2016 prompted Fisheries Queensland to request an expeditious quantitative assessment of the stock using the most up-to-date data available. Results and recommendations from this assessment are presented here. The assessment methodology was based on quantitative modelling of the stock by Campbell *et al.* (2012), which considered data from 1977–2009.

A number of assessments on the saucer scallop stock have been completed since 1996 when scallop abundance was low and recruitment in the fishery was considered to have failed:

- In 1998 an explorative age-structured stock analysis based on unstandardised data predicted strong recruitment in calendar year 1992, but was surrounded by weak estimates in 1991, 1993 and 1996 (Dichmont *et al.* 1999).
- In 2005 an age-structured stock analysis quantified reference points and predicted the exploitable biomass in the 1997 fishing year to be less than the biomass for maximum sustainable yield ($B_{1997} < B_{MSY}$), and near B_{MSY} in 1999–2001 (O'Neill *et al.* 2005). MSY was estimated near 600 t.
- In 2010 simulation modelling indicated that the SRA closed areas should not be removed and closure periods be increased to 3–4 years to ensure successive year classes and recruitment of scallop (Campbell *et al.* 2010). Investigation of fishing effort data based on VMS revealed surprisingly-high trawl intensities of 85-90% for the opening of previously-closed areas.
- In 2012 the age-structured analyses were advanced to allow for spatial aggregations and modelled long-term 1977–2009 standardised catch rates (Campbell *et al.* 2012). The results were varied depending on the complex parameters and data used. Modelling all data continuously predicted that the spawning stock ratio P_{2009}/P_{1977} was low at 27% and the stock close to recruitment overfished, but estimates increased to B_{MSY} or above when critical signals in the 1977–1987 data were moderated. MSY was estimated near 550 t.
- Also in 2012 a qualitative risk analysis was published on the likelihood of trawling reducing the population of saucer scallop below limit reference points, resulting in the fishery being classed as

overfished (Pears *et al.* 2012). The risk analysis was conducted in 2010–2011 based on literature and expert opinions from a diverse range of stakeholders. The published results suggested low risk based on species resilience and fishery impact profiles.

- In 2015 research identified associations between scallop catch rates and environmental variables, particularly Chlorophyll-a, water temperature anomalies and physical features of the Capricorn Eddy which is located adjacent to the fishery (Courtney *et al.* 2015). However, exploratory analyses using the spatial age-structured model and a subset of these environmental relationships found no evidence that they affected the survival of recruits (Madden 2016). These works are not final and the terms of reference for this assessment do not include the time or resources to further test environmental influences on saucer scallops.

2 Objectives

Summarised from project meeting 9 June 2016.

1. Summarise available data (including VMS) and past research.
2. Estimate stock status reference points: spawning potential ratio P_{2015}/P_{0}.
3. Recommendations for management and monitoring.

3 Methods

3.1 Fishing power and standardising catch rates

Full details of methods used for the fishing power analyses and catch rate standardisation are provided in Appendix 1 - Fishing power analysis and catch rate standardisation on page 26.

In brief, the standardisation was based on the application of restricted maximum likelihood models (REML) that have been used previously for the scallop fishery (Campbell *et al.* 2010). These were applied to two catch rate time series: 1) combined voluntary historical data known as HTRAWL (1977–1987) and CFISH data (1988–2016), and 2) CFISH-only data. Factors considered in the analyses included engine horse power (HP), usage of propeller nozzles, net type configuration and the use of global positioning systems (GPS) with computer mapping software, try nets, turtle exclusion devices (TEDs) and other bycatch reduction devices (BRDs). These changes and adoptions, together with the ever-changing profile of the fleet, were included in the standardisation process. Missing information on vessel fishing gears was imputed using methods described in Appendix 1 - Fishing power analysis and catch rate standardisation, section 8.4.5 on page 60.

Understanding the management history of the fishery is important for interpreting trends in the catch rates. In particular, management measures from 1977–1987 are likely to be particularly influential for explaining the relatively high catch rates at the time (Table 3-1). Pre-1988, there were a range of minimum legal sizes (MLS) in the fishery that were less conservative than those of later years, including no MLS in 1977. As a result, fishers could retain a broader size-class range of scallops, and therefore more scallops. Prior to 1984 there were no restrictions on net size. Similarly, daylight trawl bans were not trialled before October 1987. The extended hours that fishers were permitted to trawl would have contributed to higher catch rates at the time. This influence was considered in the fishing power analyses and the standardisation of catch rates. However, a lack of information on net size prior to 1984 means that the influence of net size on catch rates in the early years remains unknown. While the influence of less-conservative MLSs prior to 1988 was not considered in the catch rate standardisation process, it was included in the stock assessment model by incorporating a range of selectivity curves (Figure 9-4).

Table 3-1 Chronology of Queensland scallop fishery management.

Description	Date	Management Plan
Shell Height (SH)	1977	No minimum legal size (MLS)
	November 1980	80 mm SH
	July 1984	85 mm SH
	October 1987	90 mm SH
	March 1989	95 mm SH April–October 90 mm SH November–March
	May 1989	95 mm SH May–October 90 mm SH November–April
	Post-May 2009	90 mm year-round
Net and mesh sizes	Pre-1984	No net size restrictions
	July 1984	75 mm mesh restriction
	Post-November 1984	82 mm mesh restriction 109 m combined head and foot rope length restriction
	March 2015	Mandatory 88 mm (minimum) square mesh codend
Daylight Trawl	October 1987–December 1987	Daylight trawl ban
	Post-February 1989	Daylight trawl ban
Closures	November 1988	Designated shucking areas
	February 1989	3 10x10 minute closed areas
	May 1989	Closed areas removed
	1997–2000	3 permanently closed ‘scallop replenishment areas’
	September 2000	Southern closure (south of 22^{o}S) 20 September–30 October annually
	January 2001	Scallop replenishment areas open rotationally to trawling (Figure 9-2)

3.2 Stock assessment

To investigate the status of the scallop stock, an analysis was undertaken using the age-based population model of Campbell *et al.* (2012). The model utilised a number of data sources, including: logbook catch and effort data; the two standardised catch rate time series described above; Vessel Monitoring System (VMS) data and; the scallop fishery independent survey data. The model covers the major scallop fishing grounds and investigates change in the predicted index of abundance (informed by the standardised catch rates). A brief summary of the methods is provided below. Full details of the methods, data, population dynamics and model outputs are provided in Appendix 2 - Scallop stock assessment on page 65.

3.2.1 Data and study area

Several datasets were used in the assessment (Table 3-2), including the two standardised catch rate time series. $u^{(1)}$ is a time series of monthly standardised catch rate in baskets per boat-day (baskets boat-day^{-1}) from November 1977 to October 2015 and $u^{(2)}$ is a time series of monthly standardised catch rates in baskets boat-day^{-1} from January 1988 to October 2015. Both time series use common data for the period January 1988 to October 2015. C_{hist} is the total annual catch between 1978 and 1988 from Dredge *et al.* (2016) (Figure 9-1 Appendix 2 - page 65).

Note that the years of C_{hist} were treated as fishing years although it is likely these older data were calendar year totals. To be consistent with previous modelling of the scallop fishery (O'Neill *et al.* 2003; O'Neill *et al.* 2005; Campbell *et al.* 2012) a fishing year y is defined as 1 November of the calendar year $y - 1$ to 31 October of the calendar year y. C_{CFISH} and E_{CFISH} are monthly catch and effort, respectively from the Queensland compulsory logbook records (CFISH). E_{VMS} is the monthly effort (hrs) at 0.01 degree resolution for 2000–2015 based on the Queensland Government's Vessel Monitoring System. R_{S} is the averaged scallop density (in number metre^{-2} of scallops in the zero-plus age class) from the scallop fishery independent surveys conducted each October from 1997 to 2006.

In this study, the studied area specifically focused on an area in which 98% of effort in the CFISH data were allocated. This area was divided into 43 cells, of which 19 cells have resolution 30 x 30 minute and 24 cells have resolution 5 x 5 minute (Figure 9-2 Appendix 2 - page 66). The 30 x 30 minute resolution level is the most commonly used and coarsest spatial resolution in the CFISH data. The 5 x 5 minute cells represent the scallop replenishment areas. Additionally, the area $\mathrm{A_k}$ of cell k was calculated based on the VMS effort data such that $\mathrm{A_k}$ is the maximum value of the total area swept of the monthly effort larger than zero.

Table 3-2 Summary of datasets used for the scallop stock assessment.

Data	$\mathrm{u}^{(1)}$	$\mathrm{u}^{(2)}$	C_{hist}	C_{CFISH}	E_{CFISH}	E_{VMS}	R_s
Granularity	Month	Month	Year	Month x Grid	Month x Grid	Month x Cell	Year x Cell
Period/Range	Nov 1977 to Oct 2015	Jan 1988 to Oct 2015	1978 to 1988	Nov 1989 to Oct 2015	Nov 1989 to Oct 2015	Dec 2000 to Oct 2015 (not including Oct)	Oct of 1997 to Oct of 2006, partial spatial coverage
Sample size	456	334	11	324 x 19	324 x 19	164 x 41	430

3.2.2 Population dynamics

Campbell *et al.* (2012) proposed an age-based population dynamic model and applied it to data from the 1978 to 2009 fishing years. The general form of the population dynamics model is provided in Appendix 2 - Scallop stock assessment on page 67. Different versions of the model were developed and applied to the scallop stock by controlling the data component weightings for the log likelihood (see below). To investigate the current stock status, we applied this model to the data described in Table 3-2 above.

Allocating a weighting to each data component in the log likelihood (Table 3-3) was influential (see Population dynamics page 70) as it was used to represent the importance of a dataset (Campbell *et al.* 2012). In contrast to Campbell *et al.* (2012), the weightings of the data components ($L_{u^{(1)}}$, $L_{u^{(2)}}$,L_c, L_{Evms} and L_{R_s}) were set to represent the usage of the dataset in the model; a weighting equal to ‘1’ meant that the dataset was used in the model and a weighting equal to ‘0’ excluded the dataset (Table 3-3). For the penalty terms (L_ξ and L_ψ), small weightings were applied so that the terms had a small impact on the model results and provided numerical stabilisation. Using this weighting strategy, two models were constructed (M1 and M3). In addition, to examining how the weighting values drive the model results, a model using weightings that represent levels of (relative) importance of a dataset was also constructed (M2).

Table 3-3 Weightings for the components of the log likelihood function.

	Log likelihoods						
	Data					Penalty	
Model	$L_{u^{(1)}}$	$L_{u^{(2)}}$	L_C	L_{Evms}	L_{R_s}	L_ξ	L_ψ
M1	1	0	1	1	1	0.001	0.001
M2	0.5	0.5	1	1	1	0.001	0.001
M3	0	1	1	1	1	0.001	0.001

For all three models (Table 3-3), a weighting of 1 was allocated to L_c, L_{Evms} and L_{R_s} such that the annual catch effort from the VMS data and the recruitment survey data were used. The two penalty terms L_ξ and L_ψ were allocated small weighting values of 0.001. Specifically, model M1 was allocated weightings of 1 and 0 to $L_{u^{(1)}}$ and $L_{u^{(2)}}$, respectively. Therefore, M1 considered the catch rate information from $u^{(1)}$ but not from $u^{(2)}$. In contrast, model M3 used information on the catch rate from $u^{(2)}$ but not $u^{(1)}$. For model M2, equal weightings of 0.5 were allocated to $L_{u^{(1)}}$ and $L_{u^{(2)}}$ such that the total weighting of the catch rate is equation to 1. Hence, M2 was a model between M1 and M3 and could show how the model results were influenced by the weightings.

To verify the consistency of the results, we constructed 64 scenarios for the seven most influential parameters [$\log(\gamma)$, E_{1985}, α, ι, ϑ, ϑ_{E} and $\log(\mathrm{p})$]. For more details see Appendix 2 - Scallop stock assessment Table 9-2 page 73 and Table 9-3 page 74. Model fitting was undertaken using the ADMB program (Fournier *et al.* 2012), which facilitated construction of three phase settings (Phase 1, Phase 2 and Phase 3) for the optimisation procedure. The phase setting controls the direction of the ADMB hierarchical search for the optimisation. Hence, each model ran 192 times (64 scenarios x 3 phases). Note that given the same initial value set, the three phase settings should give similar results. Results that were not similar, possibly resulting from local optimisation, were considered as unreliable and are not reported. Details of the other model inputs, including selectivity of scallop age/size classes, the spatial closure regime, and the biological parameters are also provided in section 9.3 Stock assessment model inputs on page 72.

4 Results and Discussion

4.1 Fishing power analyses

Annual changes in relative fishing power were calculated from the REML's parameter estimates and data. The estimates were scaled as the proportional change in average catch rates relative to 1989 under constant population conditions.

4.1.1 Estimates of fishing power 1988–2016

The REML measured annual change in fishing power attributed to fixed and random components. Technologies including engine power (HP), the presence/absence of a global positioning system (GPS), try gear, net configuration (two, three, four or five nets), the presence/absence of turtle excluder devices (TEDs) and/or bycatch reduction devices (BRDs) and hours-fished were considered as fixed terms.

Change in fishing power attributed to these terms is represented by the dotted line in Figure 4-1. Fishing power changes due to fleet profile were measured by treating individual vessels (their parameter estimates) as random terms. These changes are illustrated by the difference between the overall fishing power estimate (solid line) and the fishing power estimate from the fixed effects (dotted line) (Figure 4-1). The 1989 fishing year was selected as the reference year as it was the first fishing year with complete catch records. Treating 1989 as the reference year is also consistent with O'Neill and Leigh (2006). Note again, that two lines of fishing power are presented in Figure 4-1 to illustrate which group (fixed or random) of parameters explain the results.

Fishing power increased by 15% between the 1989 and 2016 fishing years, based on the REML (Figure 4-1, including fixed and random catchability terms). If only fixed catchability terms were considered, then fishing power increased by about 20% over this period. This was driven by increases associated with vessels having higher HP, increased use of GPS and sonar, and the type of trawl gear. Fishing power was driven by more efficient vessels (measured by the vessel parameters and compared to the 1989 fleet; i.e. blue solid line is above the dotted red) rather than gear and technology effects for the fishing years 1990-1999 and 2006-2010. The fishing years 1988, 2003, 2011 and 2015-2016 showed that overall fishing power was down due to more efficient vessels (i.e. vessels with higher parameters estimates) fishing less in these years (blue solid line is below the dotted red). The Figure 4-1 graphic lines of the overall fishing power (solid line) and fishing power due to fixed terms-only (dotted line) intersected in the fishing years 1989, 2000-2002, 2004-2005, 2011-2014, indicating in these years that the fleet of vessels operating had similar vessel parameters to the 1989 fleet.

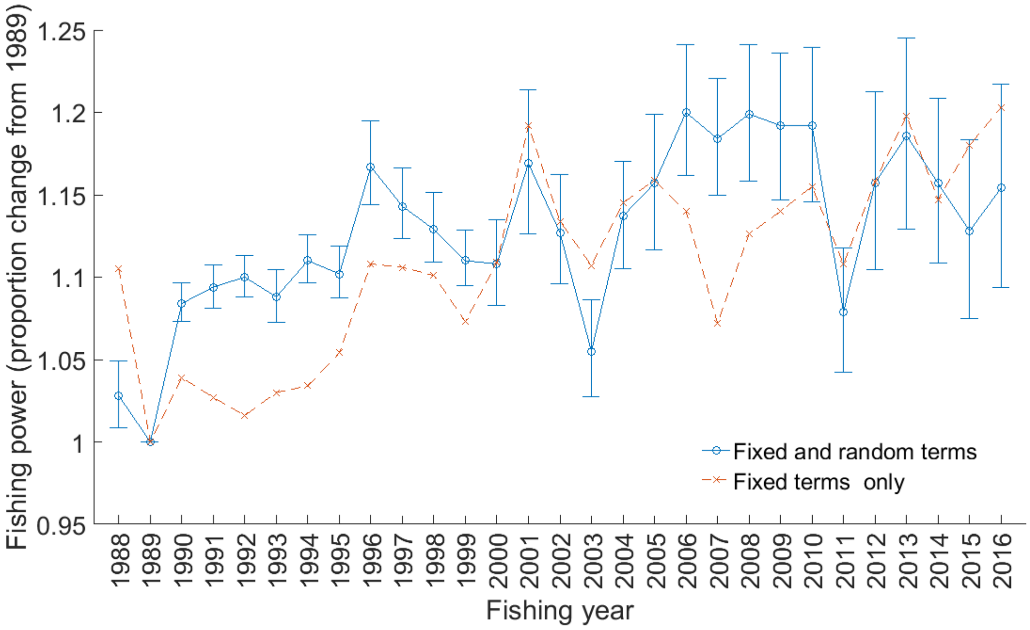

Figure 4-1 Annual fishing power trends for saucer scallops as calculated from the REML analysis on 1988–2016 data. The changes represent the mean difference from the 1989 base reference fishing year, which was set at one. Error bars illustrate the 95% confidence intervals.

4.1.2 Estimates of fishing power 1977–2016

Average fishing power increased by 16% from the 1989 to 2016 fishing years (Figure 4-2); similar to the data and result in Figure 4-1. Pre-1989 the general trend of increasing fishing power was associated with estimated increases in vessel engine HP (Figure 8-17 on page 61). From 1977 to 1989 fishing power was estimated to have increased by about 20–25%. From 1977 to 2016 estimated increases in fishing power were about 40–50%.

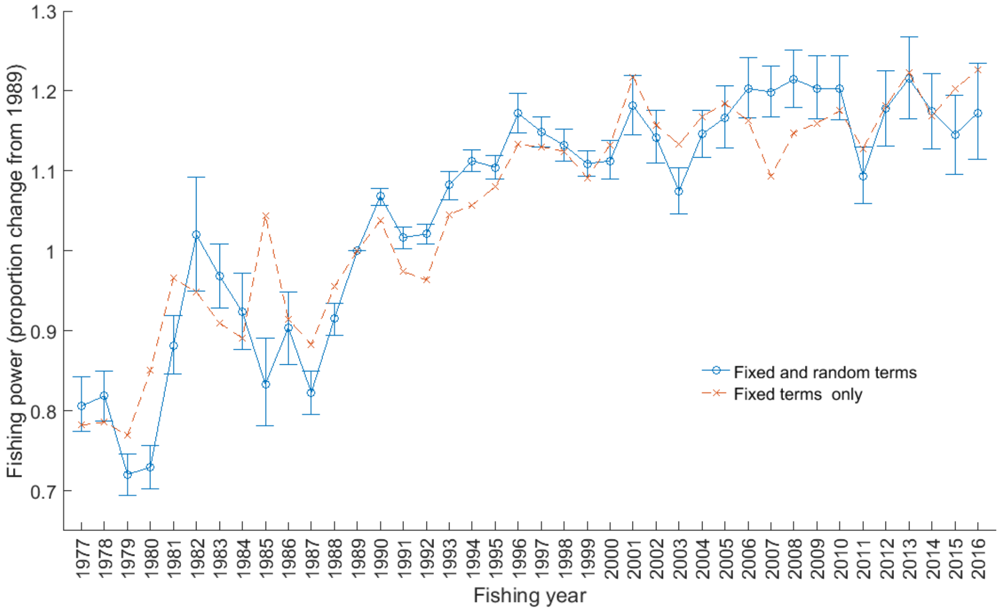

Figure 4-2 Annual fishing power trends for saucer scallops as calculated from the REML model on 1977–2016 data. The changes represent the difference from the 1989 base reference fishing year, which was set at one. Error bars illustrate the 95% confidence intervals.

4.1.3 Standardised catch rates

4.1.3.1 Standardised catch rates 1988–2016

Monthly standardised catch rates showed a general downward trend from 1988–1997, but were relatively stable from 1998–2006 (Figure 4-3). Catch rates generally improved from 2007–2013, but declined strongly after 2013. Catch rates exceeded 27 baskets boat-day^{-1} in November 2013 and declined thereafter. These relatively high catch rates were observed in several grids throughout the fishery (see Figure 4-4 and Figure 4-5 below). From January 2015 to April 2016 monthly standardised catch rates averaged 7 baskets boat-day^{-1}. In a number of fishing years, the within year declines (depletions) in catch rates were quite marked.

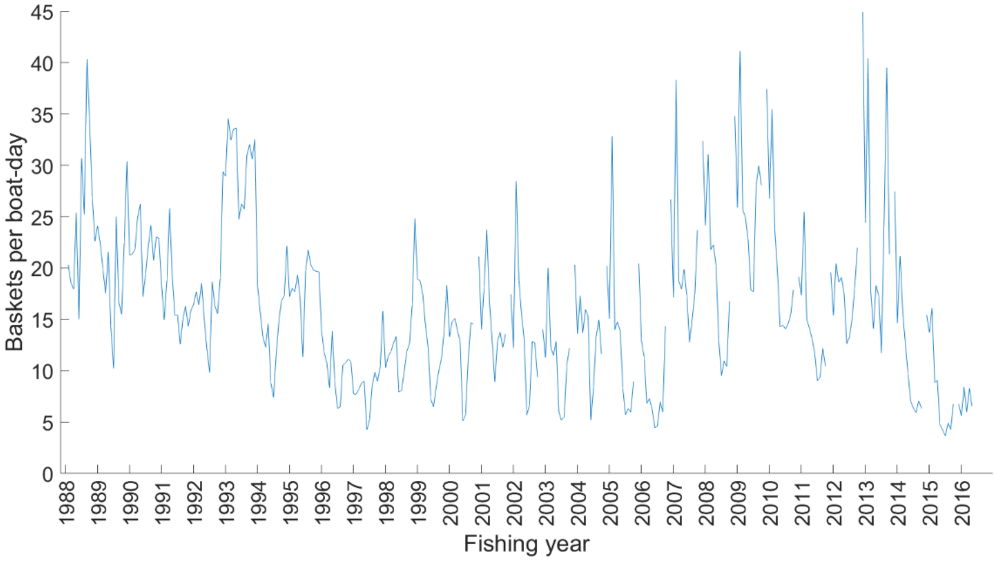

Figure 4-3 Mean monthly standardised catch rates of saucer scallops from 1988–2016. The x-axis tick marks indicate November which is the start of the fishing year. Breaks in the time series after 2000 represent the southern temporal closure which occurs from 20 September to 1 November annually. The 95% confidence intervals on mean catch rates were generally about ± 3 baskets, with a maximum of 10 baskets in April 1989.

Annual standardised catch rates have declined in recent years (i.e. 2014–2016) in nearly all fishing grids (Figure 4-4 and Figure 4-5). Catch rates in grids S28, T30 and V32 (Rockhampton to Hervey Bay), which include the scallop rotational closures, were generally reliable from 2007–2013, but thereafter declined (Figure 4-4). Catch rates for the most-southern grids W33, W34 and W35 (Fraser Island to Noosa) were variable and showed a general increasing trend from 1997–2013, but declined from 2014–2016 (Figure 4-5).

In summary, across the temporal and spatial plots of standardised catch rates (Figure 4-3, Figure 4-4and Figure 4-5):

- The trends illustrate the low catch rates taken in the years 1996–1997. This was evident in many, but not all, spatial grids.
- Catch rates were generally at their lowest from 1996–2006, but in the past were not assessed as critical over this entire time possibly due to the Scallop Replenishment Areas (SRAs) being closed and then rotationally opened to promote harvests (Table 3-1).
- In general, catch rates improved and looked up in most of the spatial grids during 2007–2013. This result suggested some recovery in the abundance of legal-size scallop. However, strong seasonal (within year) declines in catch rates are noted and this time period also corresponded with a reduction in the minimum legal size (Table 3-1).
- The main inferences and concerns now centre on the strong declines in average catch rates during 2014–2016. Significant emphasis is placed on these data, particularly with declines

calculated in many of the fishing grids. Assumptions of the analysis and differences between standardised (adjusted for patterns of fishing power) and nominal (observed and unadjusted) catch rates must be understood. The analyses consider all scallop catches boat-day^{-1} alike and that no non-targeting/avoidance behaviour by vessels in recent years biases the trends.

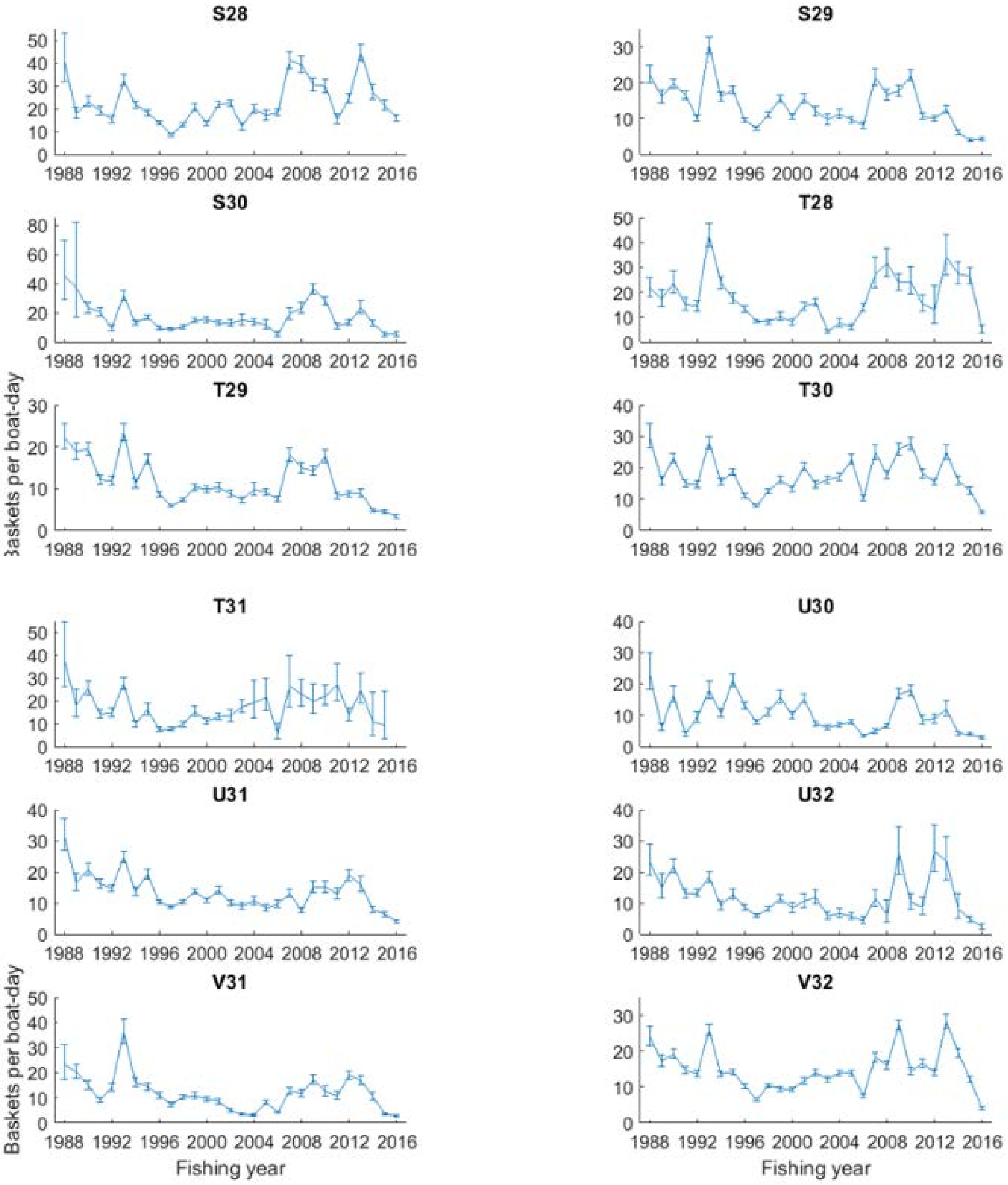

Figure 4-4 Mean annual standardised catch rates of saucer scallop from each 30 x 30 minute CFISH grid between Rockhampton and Hervey Bay. Error bars illustrate the 95% confidence intervals. Note the vertical y-axis scale varies between subplots in order to illustrate trends.

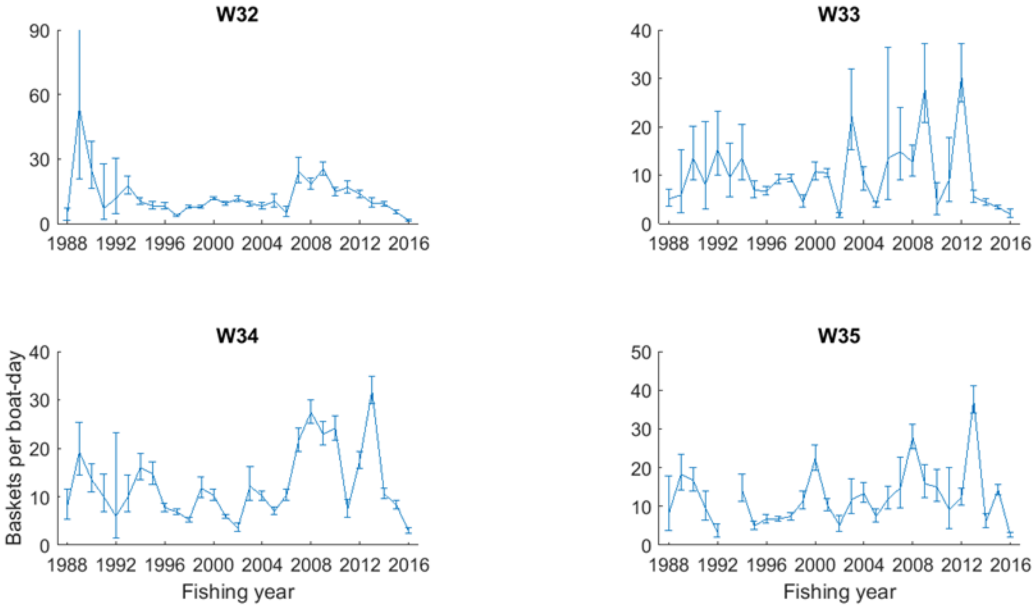

Figure 4-5 Mean annual standardised catch rates of saucer scallop from each 30 x 30 minute CFISH grid from east of Fraser Island, south to Noosa in southern Queensland. Error bars illustrate the 95% confidence intervals. Note the vertical y-axis scale varies between subplots in order to illustrate trends.

4.1.3.2 Standardised catch rates 1977–2016

The trend in long-term predicted mean catch rates shows a marked contrast between pre- and post-1988 (Figure 4-6); a compulsory logbook program was implemented from 1 January 1988. For pre-1988 fishing years, catch rates started relatively high from 1977–1978, declined in 1979–1982, spiked in 1983 and declined again from 1984–1988 (Figure 4-6). The highest monthly catch rate exceeded 200 baskets boat-day^{-1} in July 1983, although this is based on few observations (see Appendix 1 - Fishing power analysis and catch rate standardisation, Table 8-11 page 52). Standardised catch rates exceeded 150 baskets boat-day^{-1} in June 1977 and October 1979, and frequently exceeded 50 baskets boat-day^{-1} from 1982–1985. In contrast, from January 2015 to April 2016, monthly standardised catch rates averaged 5 baskets boat-day$^{-1.}$

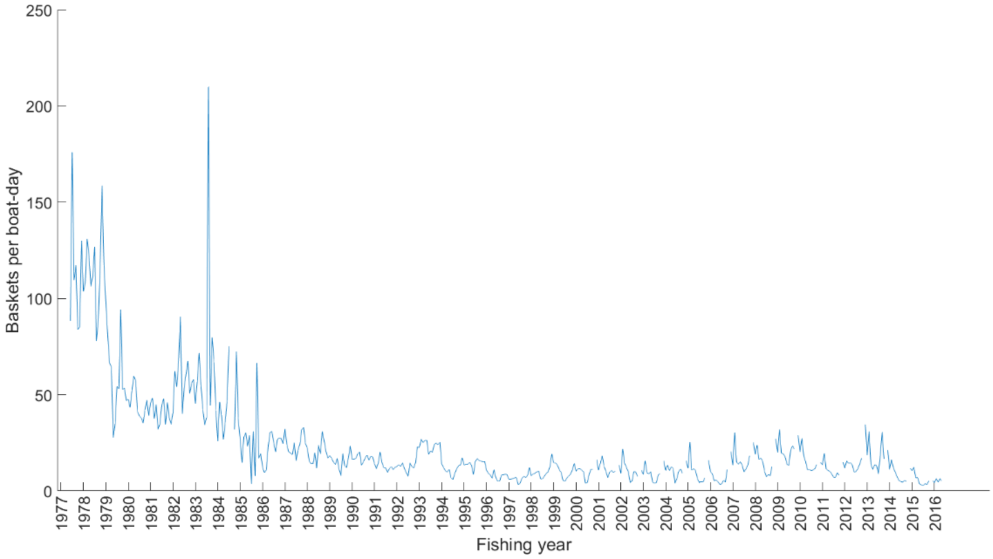

Figure 4-6 Standardised monthly mean catch rates of saucer scallops between 1977 and 2016. The x-axis tick marks indicate November which is the start of the fishing year. Breaks in the time series after 2000 represent the southern temporal closure which occurs from 20 September to 1 November annually. For comparing means, the 95% confidence intervals on catch rates were generally in the range ± 23–42 baskets pre-1988 and ± 5–8 baskets thereafter. Note the large spike in July 1983 which was based on only 3 boat days of fishing (for sample sizes see Table 8-27).

A more detailed examination of standardised catch rates from November 2013 to April 2016 and November 1995 to October 1997 is provided in Figure 4-7. A comparison is made between the recent catch rates and those of the 1996 calendar year when the fishery is considered by managers and scientists to have experienced recruitment failure, triggering implementation of three permanently closed areas (which later became the rotational scallop replenishment areas, SRAs). The data show that monthly standardised catch rates averaged about 5 baskets boat-day^{-1} from January 2015 to April 2016 (Figure 4-7). In the 1996 calendar year monthly standardised catch rates averaged about 8 baskets boat-day^{-1}, indicating the abundance of scallops in recent months was on average lower than in 1996.

Furthermore, a year-round MLS of 90 mm SH applies to the recent catch rates. In contrast, a MLS of 95 mm SH from 1 May to 31 October applied in 1996. This means that, when making a comparison with the 1996 catch rates, the recent data are inflated due to the inclusion of the additional smaller size classes (i.e. size classes between 90 mm and 95 mm SH), which were not permitted from May-October in 1996. If the recent catch rates were ‘adjusted’ to remove the contribution of these small size classes, then the averages would be lower than they appear.

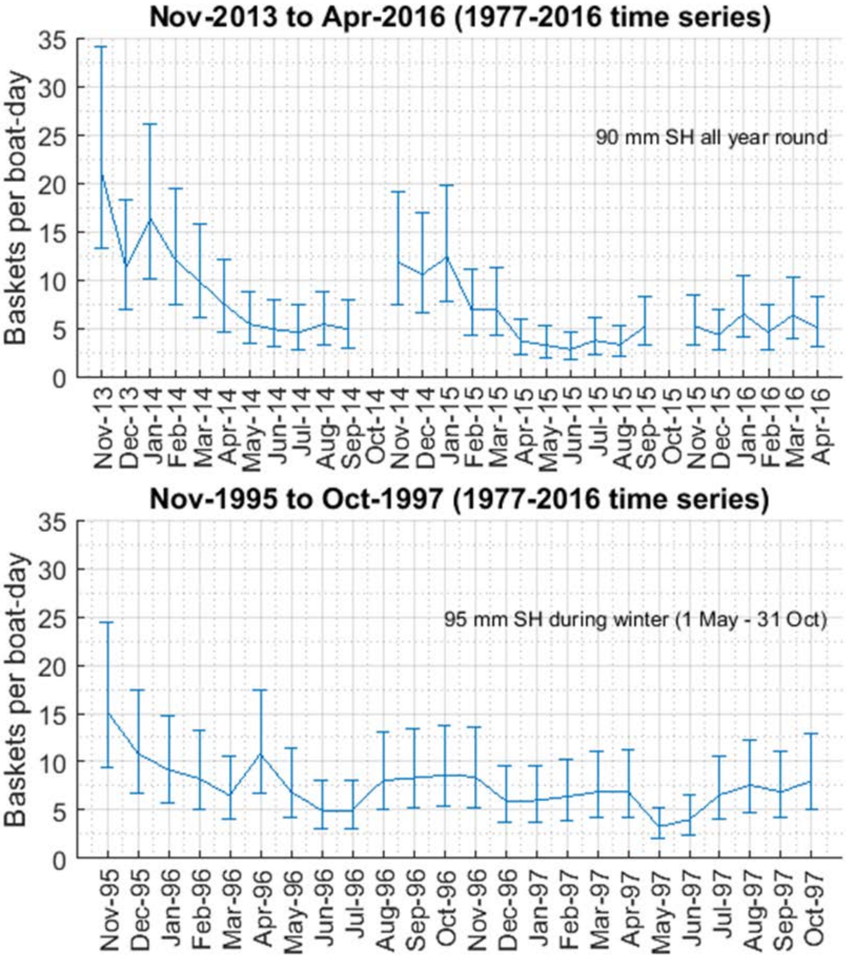

Figure 4-7 Recent standardised catch rates (upper graph) and those in 1996 and 1997 (lower graph) when scallop recruitment was considered to have failed. Error bars illustrate the 95% confidence intervals.

4.1.4 Stock assessment

A brief summary of the parameter estimates and model predictions is provided here. Further details are provided in Appendix 2 - Scallop stock assessment.

Although each model ran 192 times (64 scenarios by 3 phase settings) for sensitivity analysis, no model could successfully produce 192 results. This was mainly due to some scenarios resulting in extreme values which terminated the ADMB optimisation procedure, particularly for the model M3 scenarios. Furthermore, as M3 did not include catch rate information prior to the 1989 fishing year, it performed relatively poorly compared to M1 and M2 (see Figure 9-18, page 89).

The value for the fishing knowledge parameter γ affected the point estimates of some parameters, although its influence may not be significant because the interval estimates of those parameters overlap. Values of E_{1985}, fixed in the optimisations (Table 9-2), influenced the estimates of E_{1980} (Figure 9-5 on page 76, Figure 9-11 on page 82 and Figure 9-17 on page 88). Moreover, they affected the performance of M1 and M2 for predicting the annual catch before the 1989 fishing year. The predicted catch rates for M3 showed a poor fit to the observed catch rates prior to 1989 (Figure 9-18, page 89). This is because M3 only considers the 1988–2016 standardised catch rate time series, and therefore has no catch rate information prior to 1989 fishing year. For this reason outputs from M1 and M2 are more reliable and defensible than those of M3.

Figure 4-8 shows the spawning potential ratio P_{2015}/P_{1977} of 64 scenarios x 3 phase settings for M1, M2 and M3. For all models we assumed that the 1977 fishing year is associated with negligible exploitation. In each model, the error intervals overlap each other for each of the scenarios and phase settings. Consequently, for each model, the estimates of spawning potential ratio show little difference between scenarios as well as phases.

The general pattern in mean ratios is that M3 > M2 > M1. The high ratio of M3 is attributed to a poor estimate of spawning stock in the 1977 fishing year resulting from no catch rate information prior to the 1989 fishing year (see Figure 9-18a and d, on page 89). The reason why M2 > M1 is that although M2 has equal weighting of the two catch rate data time series, M2 gives smaller weightings for catch rates prior to 1989 fishing year. Consequently, the smaller the weighting of $L_{u^{(1)}}$, the higher the spawning ratio. For example, if the weightings given to $L_{u^{(1)}}$ and $L_{u^{(2)}}$ are 0.1 and 0.9, respectively, the spawning ratio is expected to be close to the spawning ratio from M3. These results show that the weightings can influence the spawning ratio significantly. Hence, the use of weighting to represent the importance of data should be accompanied by an awareness of its influence and sufficient knowledge or evidence to warrant its application.

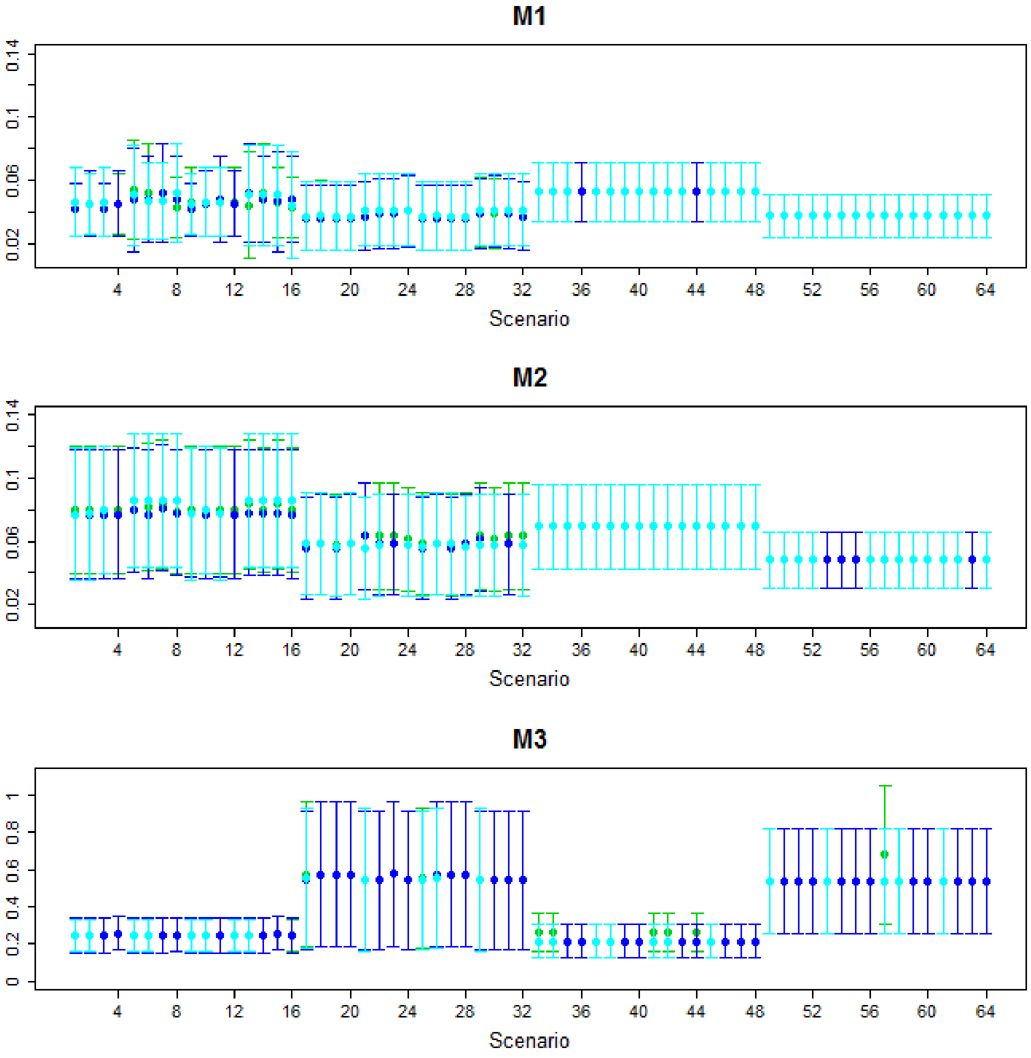

Figure 4-8 Means (solid circles) and ± two standard errors (bars) of the spawning potential ratio P_{2015}/P_{1977}. As effort in the 1977 fishing year was assumed to be negligible, P_{1977} approximates to virgin stock spawning biomass. Green, blue and light blue represent Phase 1, 2 and 3, respectively. Note the vertical y-axis scale varies between subplots in order to compare scenarios within models. To gauge the size of spawning ratios the full y-axis range 0 to 1 should be acknowledged. The error bars represent intervals of ± two standard errors.

To verify the spawning potential ratios resulting from using the current dataset (i.e. the data from section 3.2.1), the dataset in Table 3 of Campbell *et al.* (2012) was used to predict the spawning potential ratios up to 2009 for comparison. Of the three models, M2 was used to make a suitable comparison.

Figure 4-9 shows the time series of the spawning potential ratio from M2 using the current dataset and the dataset in Campbell *et al.* (2012). The error intervals of the two time series of the ratio overlap between 1978 and 2009. Although the error intervals overlap, the means of the ratio of the current dataset are larger after the 1988 fishing year. The current dataset shows that the spawning ratio has declined since 2009 (apart from increasing in 2012) to an historical minimum in 2015.

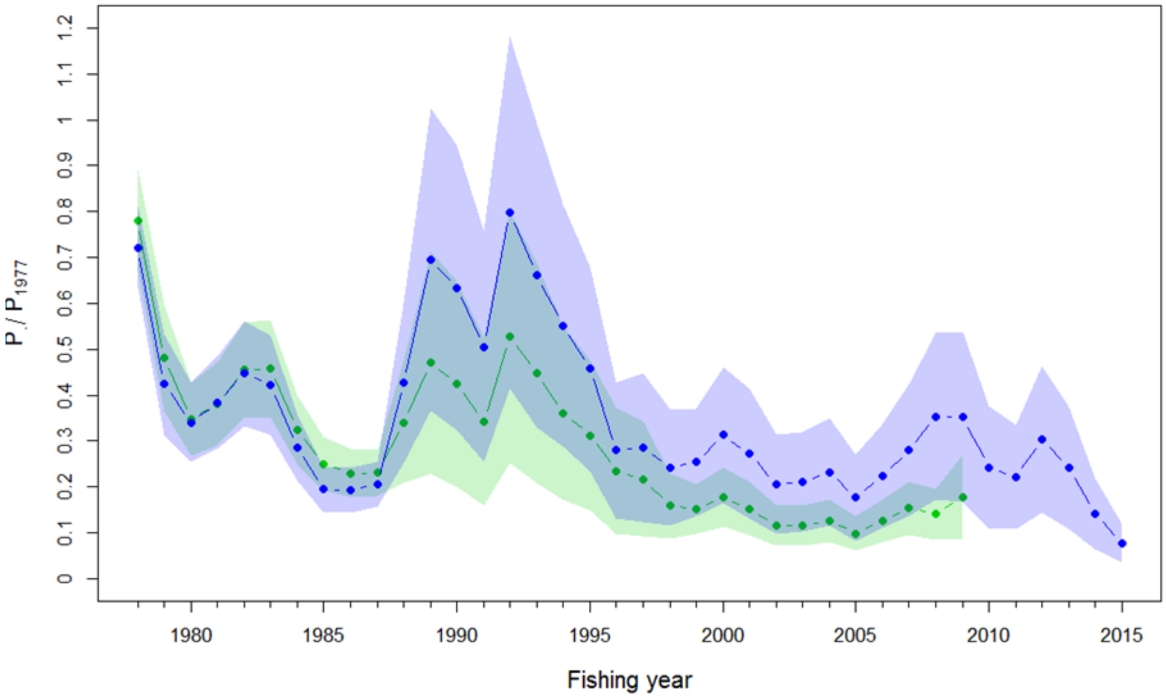

Figure 4-9 Spawning potential ratios from M2 when applied to the data of section 3.2.1 (blue) and the data (i.e. 1978 to 2009 fishing years) used in Campbell et al. (2012) (green), respectively. The solid lines represent mean ratios and the shaded areas represent intervals of ± two standard errors.

Given the estimates of the model parameters, Campbell *et al.* (2012) calculated MSY for various management scenarios. However, for our analyses, the ADMB code used by Campbell *et al.* (2012) could not produce reasonable estimates of MSY given the estimates of the parameters of M1 or M2. Reasons for this remain unknown at present. Further work is required on equilibrium MSY to verify estimates of stock productivity. This prevented us from providing any reference points pertaining to MSY.

5 Conclusions

5.1 Standardised catch rates

It is important to acknowledge that from 1977–1987 management measures in the scallop fishery were less conservative than post-1988. The standardisation largely takes account of the extended fishing hours during the early years, as well as other factors affecting fishing power. For this reason, the 1977–2016 standardised monthly catch rates should be considered as the best available index of abundance (Figure 4-6). Importantly, the long-term trend in the index is a marked decline, particularly for the last two years 2014–2015.

A detailed examination of 11 vessels that contributed logbook data during both the pre-1988 (i.e. HTRAWL data) and post-1988 (i.e. CFISH data) shows that all but one vessel experienced a long-term pattern of declining scallop catch rates (see 8.4.1 on page 52). This tends to support the above conclusion that the decline in standardised catch rates from 1977–2016 is not attributed the less-conservative management measures elevating catch rates in the early years (i.e. prior to 1988), but rather something else.

The 1988-2016 standardised catch rate time series (Figure 4-3) does not show such a marked decline in abundance as the 1977–2016 time series (Figure 4-6), but both reveal record low catch rates from January 2015 to April 2016.

The elevated standardised monthly catch rates from 1977–1987 were almost certainly partly attributed to the less-conservative MLSs during this period. While this influence was not considered in the standardising procedure, it was considered later in the stock assessment through the application of size selectivity curves (Figure 9-4).

5.2 Stock assessment

A weight-of evidence approach across model predictions and data was used to determine the stock status. The approach provided a framework to review the credibility of different results (Table 5-1). Stock status was determined by documenting the key evidence and the rationale for conclusions, and by considering the following guidelines described in Sloan *et al*. (2014), Flood *et al*. (2014) and the Australian Government (2007):

- Limit reference points (LRP): indicator values below a LRP are totally unacceptable and relate to recruitment overfishing. LRPs based on stock status ratios (i.e. S/S_0, B/B_0) default to about 20% of unfished biomass (spawning stock biomass or exploitable biomass), where B_{MSY} cannot be calculated. The Australian Government (2007) conditions state that there should be no more than 10% chance of the stock falling below the recruitment overfished LRP.
- Trigger reference points (TrRP): indicator values below a TrRP are not desirable and represent conditions where changes in management are considered and adopted. In essence, this is also a LRP. Stock status ratios for the TrRP are generally gauged to about

40% of unfished biomasses ≈ B_{MSY}. Given the complex nature of the analyses, the population MSY reference point of 40% was used to gauge the TrRP on egg production.

- Target reference points (TRP): indicator values that are desirable, safe and aspirational. They generally relate to desired economic and social objectives; e.g. a level of catch rate that is profitable and provides a quality fishing experience in terms of the number and size of scallop caught boat-day^{-1}. A proxy of $B_{50-60\%}$ was used to judge this state, which is consistent with the estimates of maximum sustainable yield by Pascoe *et al.* (2014).

For the standardised catch rate and fishing pressure indicators, limit reference levels have not been formally adopted for the scallop fishery (although data used to derive both these lines of evidence are incorporated in the stock assessment). Ad-hoc review events were used by Fisheries Queensland to assess catch rates in 2004 (O'Neill and Leigh 2006). These were defined as a trigger when early season catch rates (Nov–Feb) were less than the 70% average catch rate from 1988 to 1997. This trigger reference point incorrectly included data from the collapse in scallop catch rates in 1996–1997 and ignored depletion signals in late season catch rates.

Table 5-1 Classification of the saucer scallop stock relative to limit (red), trigger (yellow) and target (green) reference points for three key lines of evidence. (Fishing pressure includes measures of fishing effort and mortality). The colour and cross 'X' symbol indicates an activated reference point.

Evidence	**LRP**	**TrRP**	**TRP**
Standardised catch rates	X	X	
Fishing pressure	X	X	
Stock assessment	X	X	

Critical evidence, based on the data and assessment, that is used to classify the stock include:

1. monthly standardised catch rates from January 2015 to April 2016 are the lowest on record (Figure 4-6)
2. annual landings in 2014 and 2015 are among the lowest on record at 280-300 t, (Figure 9-1)
3. the spawning potential ratio P_{2015}/P_{1977} from the M1 and M2 models are approximately 5–10%.

The declining indicators of catch and standardised catch rates in recent years are consistent with overfishing using criteria presented in Fisheries Queensland (2010) and Flood *et al*. (2016). The declining indicators are also reflected in the outcomes of the Fisheries Queensland 'Status of Key Australian Fish Stocks Reports 2016' workshop in June 2016 (in press) and the current stock assessment.

Based on the guidelines described above and the results from the stock analyses, the saucer scallop fishery is assessed as recruitment overfished (Table 5-1). This conclusion is dependent on the definition of reference points and the results selected to represent the state of fishing. From the stock analyses, the probabilities are significant that the fishery has exceeded the guideline of a 10% chance of falling below 20% of B_0 ($B_{20\%}$).

The results indicate the fishery is not operating in a healthy target-state based on the lines of evidence (Table 5-1). The reference points suggest that effective management intervention across the entire scallop fishery, or a very large proportion of the fishery that accounts for the majority of the catch, is required to arrest the declining abundance and catch rates. Removing or displacing minor components of fishing effort or catch will be ineffective.

The poor condition of the stock is reflected in the declining value of monthly landings in the scallop fishery (Figure 5-1). In the 1980s and 1990s scallops dominated (70-80%) the catch value from the fishery (blue bars). In recent years (2014–2016) the monthly landed value of scallops has declined markedly. Byproduct, which is largely dominated by Moreton Bay bugs (reef bugs, *Thenus australiensis*), has always been a valuable component of the catch in the scallop fishery (yellow bars, (Figure 5-2). The monthly value of the bypoduct has remained relatively stable or increased while the value of the scallops has declined. In 2016, the monthly value of scallops has fallen to about 30%, with byproduct (predominantly Bugs) dominating the catch value.

Using 2012 fixed-price data on scallop meat, logbook data indicate that the average annual gross value of scallops from the fishery has declined from about AUD$16 million in the early 1990's to about AUD$4 million in 2014–2015 fishing years (i.e. 75% decline in value).

Two definitions of nominal fishing effort were used to examine long-term effort trends (Figure 5-2): 1) the first was based on the proportion of each boat-day attributed to scallop catch (i.e. if scallop accounted for the majority of the fisher's daily catch value, then entire day was counted as scallop effort. If scallop contributed 0.4 of catch value then the effort = 0.4 boat-day, 0.3 of value = 0.3 of boat-day, and so on), and 2) the entire boat-day was countered as effort if any scallop catch was reported (even if it comprised a minor component of the catch value). Using the latter definition (i.e. any scallop catch), nominal fishing effort declined from a peak of 19,116 boat-days in the 1995 calendar year, to a minimum of 3540 boat-days in 2015 (Figure 5-2). The difference between the two measures increases through time, indicating that byproduct is an increasingly important component of the catch and effort. Effort in recent months has been sustained by the value of the byproduct.

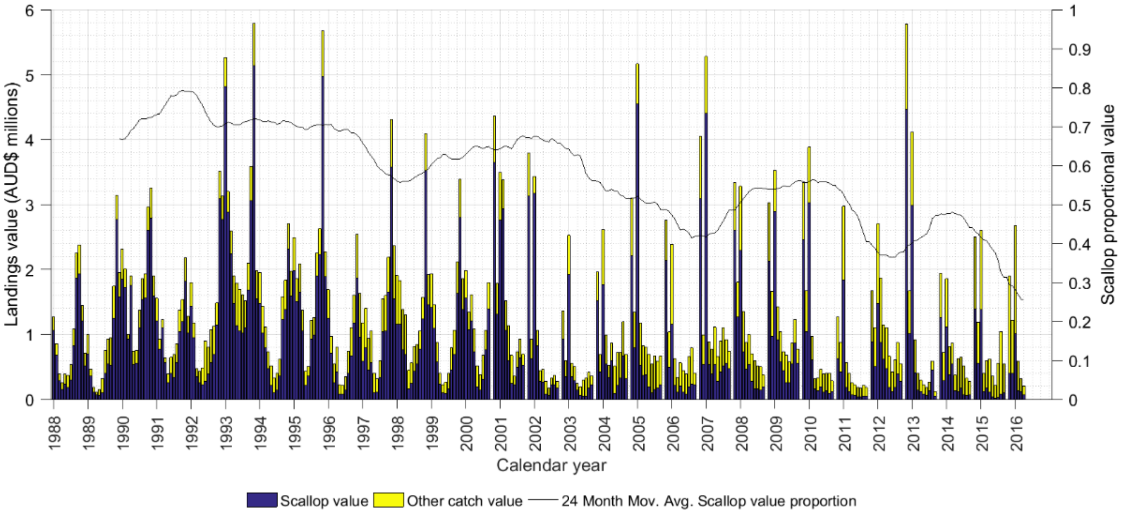

Figure 5-1 Long-term trends in the monthly value of landings in the Queensland saucer scallop fishery. The black dotted line is the 24-month average proportional contribution of scallops to total catch value. The value of landings has changed from predominantly scallops, to predominantly byproduct (i.e. Moreton Bay bugs). Seafood price data are for 2012 and were provided by the Queensland Seafood Marketer's Association and fixed throughout the time series.

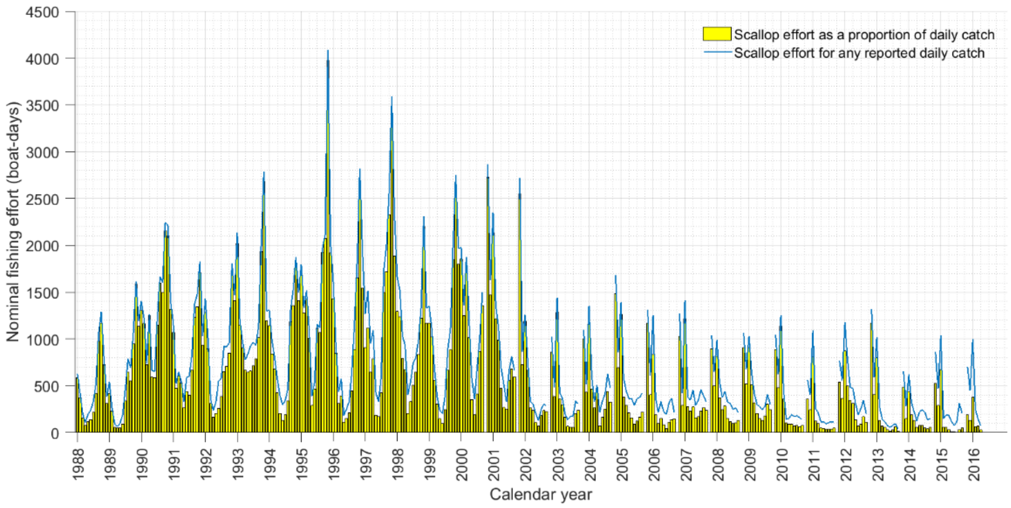

Figure 5-2 Long-term trends in the monthly nominal fishing effort in the Queensland saucer scallop fishery. Two measures of effort are provided; yellow bars (effort based on scallop proportion of catch value) and blue line (entire boat-day counted as effort for any scallop catch).

5.3 Recommendations

a) [*Management*] *Reduce fishing pressure on saucer scallop to improve abundance*
The most pessimistic results place the stock in a seriously depleted condition and if they were interpreted under the Australian Government (2007) fishery control rules, then closure of the fishery would be justified.

Based on the results, urgent measures are required to significantly reduce fishing effort in order to allow the stock to rebuild. Minor changes to effort, catch or minimum legal sizes will be insufficient. New management measures will need to consider different procedures that assume a precautionary stock-size estimate and appropriate limits to the number of vessels and effort. Walters and Martell (2004) discuss generic management options and concepts that can apply to saucer scallops.

Well-designed fishery-independent surveys of scallop abundance (undertaken at least annually) would be of benefit to validate stock status, track recovery of the stock and inform future management arrangements; but awaiting this information should not be a reason to delay action.

A formal harvest strategy, consistent with the reforms proposed in the recent Green Paper on fisheries management reform in Queensland, would be of benefit, including clear limits and target reference points and harvest control rules.

Recent research has demonstrated some associations between scallop standardised catch rates and freshwater flow, chlorophyll-a, water temperature and properties of the Capricorn Eddy which is located adjacent to the scallop fishery (Courtney *et al.* 2015). However, additional time and resources are required to examine these relationships further and their meaning for management.

b) [Monitoring] 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 technologies have been included in this assessment, but there are others that have not been included due to lack of information. In many fisheries there are advances in technologies in addition to those assessed in this report. The challenge will be to adequately model fishing power, as it will continue to increase as a response to ongoing technological advancement.

c) [Monitoring] Validate records of daily fishing effort and harvest in logbooks
Improving validation of catch data is a current priority for fisheries management across all commercial fisheries. Improved information on hours fished, the fishing gear used, and precise fishing location information (through VMS/GPS) will enable modelling of the changing dynamics of fishing and produce better indices of abundance. Dedicated work is also required to further analyse the HTRAWL catch rate data for the years 1977–1987. The quality of the HTRAWL data could be slightly

improved by further checking and validating to eliminate records that have multiple daily catch records due to the vessel being allocated multiple BRNs on a single day.

d) [*Monitoring*] *Conduct a fishery independent survey*

The government and industry need to discuss the costs and benefits of conducting a robust fishery independent abundance survey of fishing grounds to validate stock status and to optimise management procedures.

e) [*Stock assessment*] Future assessments of the scallop fishery could be improved by considering the following:

- Although some associations have been demonstrated recently between standardised scallop catch rates and environmental conditions on the Queensland coast (Courtney *et al.* 2015), no environmental variables were considered in the current assessment, due to the urgency of the assessment and because it would have required significant additional time and resources to modify the model. Future assessments should include one or more key environmental variables – this was also a recommendation of the FRDC 2013/020 project final report (Courtney *et al.* 2015).
- The LTMP fishery-independent survey data (1997–2006) are a highly valuable reference dataset for the scallop fishery. A complete version of the raw survey data, including details of each of the 10 annual surveys, needs to be made available to derive robust estimates of abundance.
- The study showed that the weightings applied to the likelihood components significantly influence the results. Further investigation of how the models can be modified to better use the data is warranted.
- The model needs to be transferred to other software such as Matlab to further the modelling and visualisation of hypotheses that need to be tested and to calculate new reference points such as MSY and MEY.

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7 Acknowledgements

The work was overseen by a committee that consisted of the authors and the following Fisheries Queensland staff; Darren Roy, John Kung, Michael Mikitis and Brad Zeller who provided fisheries management advice, and Nadia Engstrom who assisted with the fishery data extractions and discussions of those data. Warwick Nash and Veronica Robinson (Animal Science, Department of Agriculture and Fisheries) and Kaye Basford (University of Queensland, Centre for Applications in Natural Resource Mathematics, CARM) provided constructive comments on the report.

8 Appendix 1 - Fishing power analysis and catch rate standardisation

This section of the report addresses the catch rate standardisation process for saucer scallops for the periods 1988–2016 and 1977–2016, respectively.

8.1 Introduction

The standardisation was based on the application of restricted maximum likelihood models (REML) that have been used previously for the scallop fishery (Campbell *et al.* 2010). These were applied to two catch rate time series 1) combined ‘historical data’ (1977–1987) and CFISH data (1988–2016), and 2) CFISH-only data. Factors considered in the analyses included engine power (HP), usage of propeller nozzles, net type configuration and the use of global positioning systems (GPS) with computer mapping software, try nets, turtle exclusion devices (TEDs) and other bycatch reduction devices (BRDs).

Understanding the management history of the fishery is important for interpreting trends in the catch rates. In particular, management measures from 1977–1987 are likely to be particularly influential for explaining the relatively high catch rates at the time (Table 8-2). Pre-1988, there were a range of minimum legal sizes (MLS) in the fishery that were less conservative than those of later years, including no MLS in 1977. As a result, fishers could retain a broader size-class range of scallops, and therefore more scallops. Prior to 1984 there were no restrictions on net size. Similarly, daylight trawl bans were not trialled before October 1987. The extended hours that fishers were permitted to trawl would have contributed to higher catch rates at the time. Some of these factors, such as daily hours-fished were accounted for in the fishing power analyses. Some factors, such as the variation in net size were not able to be considered due to a lack of data. Variation in the MLS was not considered in the catch rate standardisation process, but was accounted for later by applying selectivity curves in the stock assessment model.

Several datasets were used in the statistical analyses undertaken to derive fishing power changes and standardise catch rates. Table 8-1 provides the name and a description for each of the datasets.

Table 8-1. List of datasets and their descriptions.

File name	File type	Description
stock status updates.mdb	MS Access	Scallop catch rate and fishing gear data for 1988 to 2015 analysed as part of the 'Status of Key Australian Fish Stocks Reports 2016' (in press with FRDC; http://fish.gov.au/Pages/default.aspx)
Scallop raw data to send Nadia.mdb	MS Access	Scallop catch rate data for all years 1988 to 2016. The 2016 data was appended to 'stock status updates' to complete the time series 1988 to 2016.
HTrawl2000.mdb	MS Access	The main HTRAWL database for voluntary historical prawn and scallop catch rates (1977 to 1988); also simply referred to as HTRAWL.
glmdata.gsh	Genstat	The voluntary historical scallop catch rate data analysed from the HTRAWL database (1977–1987). These data were analysed in the previous stock assessment for scallop (O'Neill and Leigh 2006).
revised glmdata.gsh	Genstat	The same data as in glmdata.gsh except the hours fished were reviewed and corrected as necessary (Table 8-6).
revised glmdata 11 key.gsh	Genstat	From 'revised glmdata.gsh', data for the 11 key vessels that fished pre- and post-1988 that were investigated (Table 8-6).
REMLdata1988to2016.xlsx	Excel	The scallop catch rate and fishing gear data 1988 to 2016 for Genstat analysis.
REMLdata1977to2016.xlsx	Excel	The scallop catch rate and fishing gear data 1977 to 2016 for Genstat analysis. This dataset combined revisedglmdata.gsh and REMLdata1988to2016.xlsx.

8.2 Methods

8.2.1 Processing the catch and effort data

Two data sources were used to compile the time series of scallop catch rates. The first data source was the Queensland compulsory CFISH trawl logbook records from 1 January 1988 to 30 April 2016. These data included scallop total harvest, fishing effort and catch rates. The second data source was based on voluntary trawl logbook records that were mainly initiated through research projects prior to 1988 and are collectively referred to as the historical catch rate data or HTRAWL. Standardised catch rates were calculated from 1) the CFISH-only data; and 2) the combined CFISH and HTRAWL data. The following describes the processing rules applied to the data.

Table 8-2 Chronology of Queensland scallop fishery management.

Description	Date	Management Plan
Shell Height (SH)	1977	No minimum legal size
	November 1980	80 mm SH
	July 1984	85 mm SH
	October 1987	90 mm SH
	March 1989	95 mm SH April–October 90 mm SH November–March
	May 1989	95 mm SH May–October 90 mm SH November–April
	Post-May 2009	90 mm year-round
Net and mesh sizes	Pre-1984	No net size restrictions
	July 1984	75 mm mesh restriction
	Post-November 1984	82 mm mesh restriction 109 m combined head and foot rope length restriction
	March 2015	Mandatory 88 mm (minimum) square mesh codend
Daylight Trawl	October 1987–December 1987	Daylight trawl ban
	Post-February 1989	Daylight trawl ban
Closures	November 1988	Designated shucking areas
	February 1989	3 10x10 minute closed areas
	May 1989	Closed areas removed
	1997–2000	3 permanently closed ‘scallop replenishment areas’
	September 2000	Southern closure (south of 22° S) 20 September–30 October annually
	January 2001	Scallop replenishment areas open rotationally to trawling

8.2.1.1 CFISH trawl data

The catch rate data were based on scallop catch and effort records from 1 January 1988 to 30 April 2016 and consisted of daily catch and effort (in hours-fished) for each individual vessel. The spatial resolution of catches was 30 x 30 minute latitudinal and longitudinal grids. CFISH data from 1 January 1988 to 31 December 2015 were provided in a Microsoft Access file called ‘stock status updates.mdb’ supplied by data request DR2457. CFISH data for 1 January 2016 to 30 April 2016 were appended to the ‘stock status updates’ database from the Access file called ‘Scallop raw data to send Nadia.mdb’. The procedures applied to the data are detailed in Table 8-3. The fishing year for scallops was defined as 1 November to 31 October based on the life cycle, time and size at recruitment, and the seasonal variation in fishing effort.

Pre-2004, 344 past and present vessel owner/operators were interviewed and completed a questionnaire quantifying the adoption rates of technologies affecting fishing power in the major Queensland fishing sectors (i.e. the eastern king prawn, scallop, north Queensland tiger/endeavour prawn) (O'Neill *et al.* 2005). Since 2004, similar information on usage of vessel gear and technology has been provided by fishers and recorded with their logbook data. The database ‘stock status updates.mdb’ thus merged these two data sources on vessel gears and technologies, which included the presence or absence of Kortz nozzle, sonar, GPS, try gear, TEDs and BRDs, and information on engine size (HP), net type configuration, total net head rope length, net mesh size, ground gear type, otter-board type and trawling speed.

Table 8-3 Data procedures used to define saucer scallop data used for catch rate analysis.

Data	Details	Notes
CFISH data extraction	All data collated 7 July 2016 by access file	CFISH data for 1 January 1988 to 30 April 2016 where there is gear information for vessels
Time period for analysis	1 January 1988 to 30 April 2016	
Daily records	Only daily records were analysed. A daily record has the same fishing start date and fishing end date.	
Harvest Conversions	Catch rates were reported as the number of baskets of scallops. These were later converted to scallop meat weight for stock assessment modelling.	
Fishing year	Defined from 1 November through to 31 October	
Stock or fishing area	Single area: this covered the main fishing waters of east-coast latitudes south of 22° S inclusive and north of 26.5° S inclusive	
Logbook grids analysed	V32, T30, S28, S29, U31, T29, U32, S30, V31, T31, U30, W34, W32, W33, W35	These 30x30 minute logbook grids represent 95% of the total harvest
Months with limited data	October in the calendar years 2000 to 2016.	For the southern trawl closure (20 September to 1 November annually, commenced in 2000)
Fishing method codes	FishingMethodTypeId=7	Identifies otter-trawling
Saucer scallop species codes	caabspeciesid=23270001	
Excel file for GenStat analysis	‘REMLdata1988to2016.xlsx’	Data was exported from MS Access

8.2.1.2 Historical trawl data

The historical scallop trawl data (HTRAWL) is stored in the file ‘glmdata.gsh’. These data represented voluntary logbook catch data collected between 1977 and 1987 prior to the implementation of the compulsory CFISH logbook system in 1988. 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.

Note the comments in the 1999/120 final report (O'Neill *et al.* 2005) about the historic data (section 8.3.7, page 94): '*Logbook catch data prior to the implementation of the compulsory QFISH logbook system in 1988 are of varying quantity and quality. To extract these data in a compatible form for comparison with current data obtained from the QFISH system, considerable cleaning and transformation were required. Historical trawl data consists of all the scallop and prawn records obtained from approximately 16 sources. These data reside in the HTRAWL database within the QFISH system. Of these records only a subset were finally used in the statistical analyses.'*

Questions were raised in FRDC Project No 2006/024 (page 42) (Campbell *et al.* 2010) about whether the historic data were representative: '*The pre-1988 catch rates were significantly higher than those from the post-1988 period, with standardised catch rates (predicted from the REML) exceeding 50 baskets per vessel per day on a number of occasions. However, whether this is an accurate measure of abundance is disputable, given the data used to generate Figure 8-14 were based on voluntary logbooks. As such, only those fishers that wanted to participate in the logbook scheme submitted catch data. It is, therefore, difficult to ascertain whether these data are based on an 'average' vessel. Anecdotal evidence suggests that only 'good' fishers participated in the voluntary logbook scheme, which may have artificially inflated catches during the pre-1988 period*.' The relatively high pre-1988 catch rates may also reflect that there was no minimum legal size (MLS) for scallops prior to 1980, and that a MLS 80 mm shell height (SH) was implemented in 1980, and increased to 85 mm SH in 1984 (Table 8-2). Other factors that may have contributed to the elevated daily catch rates pre-1988 include possible usage of larger nets, as well as the extended number of hours-fished per day.

As a result the HTRAWL data were investigated in order to determine if there was further evidence to support or dispute the decreasing trend in standardised scallop catch rate (baskets boat-day^{-1}), predicted from the REML model where boat_mark and boat_mark*fishing year are random factors, and loghours, fishing_year*month, grid, logprawns, lunar and lunar_adv are the fixed factors (O'Neill and Leigh 2006).

As no new data could be added between 1977 and 1988, it was decided to look more closely at the trends in catch rates of individual vessels that were common in the HTRAWL data and the CFISH data. The logic behind this decision was that 'good' fishers from the pre-1988 data should still be 'good' fishers post-1988, if their vessel and owner or skipper had not changed. Eleven vessels were selected for further investigation of their catch data and catch rates over time. These 11 vessels were considered to have a reasonable number of days fishing in both the HTRAWL and CFISH datasets as well as reasonable catches of scallops. Section 8.4.1 on page 52 describes the methods used to select these 11 vessels.

During the investigation of the catch time-series of the 11 individual vessels, two types of error were identified in the aggregation of HTRAWL data that then formed the records in 'glmdata.gsh'. A record was defined as a single row in ‘glmdata.gsh’ with the following fields, boat mark, baskets (summed daily catch for the boat mark), fishing date, grid, hours-fished, lunar phase, and lunar phase advanced.

Error type 1

There was no specification within HTRAWL whether the field ‘fishing time’ was in hours or minutes. However, 35 records in HTRAWL of aggregated daily catch and effort per vessel had a total ‘fishing time’ greater than 24.0. It appeared to have been previously assumed that ‘fishing time’ greater than 24.0 was in minutes whilst ‘fishing time’ less than 24.1 was in hours. This resulted in large spikes in scallop catch rate per hour for these records (Table 8-4), which are unlikely to be real. For these 35 records, hours-fished (in ‘glmdata.gsh’) were adjusted to 24.0. The 35 records were 0.4% of the total number of records in ‘glmdata.gsh’, and thus this error was unlikely to have a significant effect.

Table 8-4 Example of error type 1 in the aggregation of historic daily scallop catch and effort data for a single vessel (HTRAWL) and implications for catch rate (baskets per hour) in ‘glmdata.gsh’.

Date	**Baskets**	**Fishing time**	**Baskets per hour**	**Source**
19/08/1978	293	0.405	732.5	‘glmdata.gsh’
19/08/1978	293	24.3	12.1	‘HTrawl2000.mdb’

Error type 2: unclear how many records

Some vessels appeared to have multiple daily records of catch in HTRAWL because they had more than one boat record number (BRN) in overlapping time periods, resulting in aggregated ‘fishing time’ greater than 24.0 in ‘glmdata.gsh’, as per error type 1 (Table 8-5). There were 54 daily records where hours-fished was greater than 24.0 but it was not clear if these were all error type 2. This should be investigated further.

Table 8-5 An example of error type 2 where multiple boat record number, BRN, assignments for a single vessel on a single day in HTRAWL were aggregated into a single record in ‘glmdata.gsh’.

Date	Baskets	Fishing Time	Source
11/09/1977	120	22	HTRAWL
11/09/1977	102	11	HTRAWL
11/09/1977	222	33	‘glmdata.gsh’

The original REML command file (see section 8.4.3 page 56) for catch rate standardisation used in FRDC Project No 2006/024 was run on three data sets shown in Table 8-6.

Table 8-6 Datasets for REML analysis.

Data	Comment
'glmdata.gsh'	Previous stock assessment for scallop used this data set (O'Neill and Leigh 2006)
'revised glmdata.gsh'	Hours fished in HTRAWL > 24.0 were adjusted back to 24.0 (as per error type 1). Thirty-five records were changed; with these records being identified by the difference between hours_orig and hours_revised greater than zero in the data file.
'revised glmdata 11 key.gsh'	Data file for the 11 key vessels outlined in section 8.4.1 whose individual catch history was investigated in the current study and who were considered to be the same vessel, with the same owner or skipper between the historic trawl data (1977–1987) and the early part of the CFISH data (i.e. 1988–2000).

Similar patterns of declining catch rates over time were produced by the REML model with the revised data using both all vessels and the 11 key vessels.

Thus, the detailed investigation of the available historic data provided no evidence to contradict the declining trend in standardised catch rates in the scallop fishery originally reported in O'Neill and Leigh (2006). While the REML models consider hours-fished as a fixed term, there were other management measures in the 1977–1987 period in addition to 24-hour fishing that also contributed to the elevated catch rates at the time. For example, pre-1980 there was no minimum legal size (MLS), or reduced MLS limits, thus allowing fishers to retain more scallops in their daily catches (Table 8-2). In addition, it was possible that larger nets were used and slower trawl speeds adopted pre-1980.

It should also be noted that the HTRAWL data are spatially and temporally limited, particularly in comparison to the CFISH data, and that the current investigation did not exclude the possibility that the historic data are biased or non-representative, in regards to time and space. Table 8-11 in section 8.4.1 page 52 highlights the patchiness of the historical data by (calendar) year and month, particularly the low sample sizes in 1984 and 1985. However, some confidence in the observed declines in standardised catch rates should be taken from data from the early years of the historic data. The (calendar) years 1977–1980 (inclusive) had data from more than 40 vessels per year (thereby capturing a range of fisher ability) as well as more than 750 daily fishing effort records per year (thereby capturing a range of spatial and temporal variability in the scallop fishery).

In addition, the investigation highlights the possibility of aggregation and multiple attribution errors in the historic data (error type 2) that are a consequence of the difficulty in tracking individual vessels over time as well as the difficulty of combining old and new data sets into a single time series.

The historical trawl data file used for the present analysis is called ‘revisedglmdata.gsh’. The data file had 9161 rows and applied from 1 January 1977 to 31 December 1987.

8.2.2 Statistical Analyses

8.2.2.1 CFISH trawl data

The CFISH trawl data consisted of 124 974 daily vessel catch records of which 8754 records (7%) had no information on fishing-hours. The missing hours were imputed from an over dispersed Poisson model with a random variation (section 8.4.2 page 54).

The statistical analysis adopted the REML from O’Neill and Leigh (2006) assuming normally distributed errors on the log scale (Montgomery 1997; VSN International 2013). Section 4.3.2.1 of O’Neill and Leigh (2006) provided a detailed derivation of the mathematical equations and discussed the advantages of using REML rather than a generalised linear model.

This analysis used the model with the same form as equation (2) in O’Neill and Leigh (2006). Therefore the catch (baskets) taken on day i by the vth vessel in grid a, during fishing year y and month m was modelled as:

$$\log_e(C_{ivaym}) = \beta_0 + \sum \boldsymbol{\beta}_1 \mathbf{X}_1 + \sum \boldsymbol{\beta}_2 \mathbf{X}_2 + \boldsymbol{\gamma} \mathbf{Z} + \varepsilon \tag{8-1}$$

where β_0 was a scalar intercept parameter to be estimated, $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_2$ were vector parameters to be estimated for abundance and fishing power. $\mathbf{X}_1$ and $\mathbf{X}_2$ were the corresponding data, ε was the error term, γ was a vector of random effects for different vessels and fishing grids, $\mathbf{Z}$ indicated which daily catches belonged to each vessel and grid, and $\boldsymbol{\Sigma}$ were summation symbols. The factors affecting fishing power, $\boldsymbol{\beta}_2$, were represented by the variables of hours (fished), HP, sonar, GPS, net type and ground gear. The following factors were excluded from the REML model either due to their non-significance or correlation with other factors (section 8.4.4 page 56) (Bishop *et al.* 2008); nozzle, boards, lunar, lunar advanced, BRDs and TEDs, try gear, net size and trawl speed.

The $\boldsymbol{\beta}_2$ parameters and vessel components of the model in equation 8-1 were the focus of interpretation for calculating annual changes in fishing power. As in O’Neill and Leigh (2006) relative fishing power was calculated as a proportional change in average catch rates from fishing-year to fishing-year under standard conditions. The methods were explained on page 23 in O’Neill and Leigh

(2006). In addition, the parameter estimates for $\boldsymbol{\beta}_2$ were used to include gear and technology effects for the 1977–2016 REML model (section 8.2.2.2 page 34).

The result from the abundance vector, $\boldsymbol{\beta}_1$, specifically the interaction between year and month terms, was used to calculate standardised catch rates to represent changes in scallop abundance.

The statistical software package GenStat 16th edition (VSN International 2013) was used to carry out the analysis. GenStat code for the REML analysis is in section 8.4.4 page 56.

Estimating relative fishing power

Annual changes in average relative fishing power were calculated from the linear mixed model (REML) with the number of baskets boat-day^{-1} as the response variable. The methods were outlined on pages 22 and 23 in O'Neill and Leigh (2006). The equation on page 23 was used to write the expected catches as

$$c = \exp(\sum \boldsymbol{\alpha}\mathbf{X} + \boldsymbol{\gamma}\mathbf{Z}) \qquad \text{8-2}$$

where within $\boldsymbol{\alpha}$, $\boldsymbol{\beta}_2$ was the vector of catchability coefficients (from equation 8-1), γ was a vector of random vessel terms with design matrix $\mathbf{Z}$, and exp was the exponential function. β_0, $\boldsymbol{\beta}_1\mathbf{X}_1$ within α and grid with $\mathbf{Z}$ were constant in the prediction to separate changes in abundance from fishing power.

Following O'Neill and Leigh (2006) the annual changes in relative fishing power were written as

$$\mathbf{f} = \frac{\bar{\mathbf{c}}}{\bar{c}_{1989}} \qquad \text{8-3}$$

where $\mathbf{f}$ was the vector of proportional change in average catch rates relative to 1989, $\bar{\mathbf{c}}$ was the vector of annual average catch rates under standard conditions, and to be consistent with O'Neill and Leigh (2006) the average expected catch rate in 1989, $\bar{c}_{1989}$, was used as the reference fishing year.

8.2.2.2 Historical trawl data and CFISH data

A total of 9561 HTRAWL daily vessel catch records, (from 'revised glmdata.gsh') were appended to the 124 974 records of CFISH data to give a total of 134 535 rows of data in 'REMLdata1977to2016.xlsx'. There were no missing data for hours-fished in HTRAWL data. The 8754 records with missing hours in the CFISH data were imputed using the Poisson model from the linear mixed model 1988–2016 (section 8.4.2 page 54). Figure 8-1 shows the distribution of fishing hours boat-day^{-1} after the missing hours were imputed. Note that there were still 54 records in HTRAWL where hours fished was greater than 24.0 and it was not clear if these were all error type 2 (section 8.2.1.2 page 29). These records were not changed, hence whiskers in the box plot extended beyond 24 hours.

The REML model for the 1977–2016 dataset (section 8.4.6 page 61) was different from the 1988–2016 model (section 8.4.4 page 56) because the HTRAWL data do not include information on vessel gears or technology. The REML model 1988-2016 had as fixed terms log(hours), log(HP), GPS, sonar, net type, and ground gear, (these fields were available in the 'stock status updates.mdb' database file), and generated linear predictors for these parameters. Rather than exclude gear and technologies in the 1977–2016 analysis, the REML model included vessel gear and technology effects for 1977–2016 using the values of the linear predictors from the REML model 1988–2016.

Thus HP, sonar, GPS, net type and ground gear were imputed for HTRAWL data using methods outlined in section 8.4.5 page 60. The analysis of HTRAWL and CFISH data was then taken for a full time series of data from 1977–2016, where hours fished boat-day^{-1} were imputed for the CFISH data and sonar, GPS, ground gear, net type, and HP were imputed for HTRAWL data. The final Microsoft Excel file used for the GenStat analysis was 'REMLdata1977to2016'.

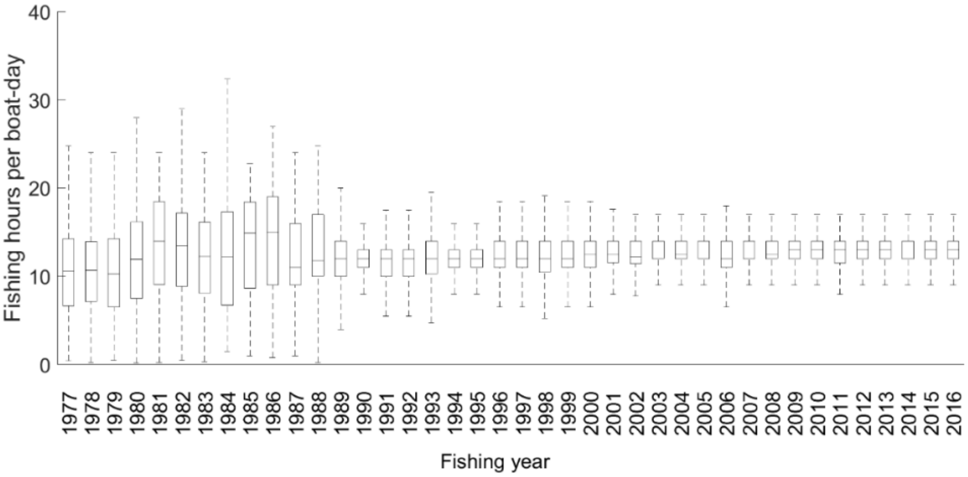

Figure 8-1 Box and whisker plot of fishing hours boat-day^{-1} after missing hours in CFISH were imputed. The centre box line is the median. The whiskers, i.e. the lines extending above and below each box, extend from the ends of the interquartile ranges to the furthest observations within the whisker length of 1.5 times the interquartile range. The outliers (data beyond the whisker length) are not shown. Hours greater than 24 in HTRAWL data (1977–1988) were corrected for 35 records as per error type 1 in section 8.2.1.2. However, there were 54 daily records in HTRAWL where hours fished were greater than 24.0 but it was not clear if these were all error type 2 (section 8.2.1.2).

The gear and technology parameter estimates $\boldsymbol{\beta}_2$ from equation 8-1 from REML analysis 1988–2016 were used to adjust (offset) the catch (number of baskets) for the analysis 1977–2016 as

$$\log_e(C_{ivaym\_offset}) = \log_e(C_{ivaym}) - \sum \boldsymbol{\beta}_2 \mathbf{X}_3 \qquad \text{8-4}$$

where C_{ivaym} was the catch (baskets) taken on day i by the vth vessel in grid a, during fishing year y and month m, $\boldsymbol{\beta}_2$ was the vector parameter estimated for factors affecting fishing power from the REML model 1988 to 2016, $\mathbf{X}_3$ was the corresponding data for HP, sonar, GPS, ground gear and net type, C_{ivaym_offset} was the catch (baskets) with the gear and technology offsets. The statistical software package GenStat 16th edition (VSN International 2013) was used to carry out the analysis. GenStat code for the REML analysis 1977–2016 is provided in section 8.4.6 on page 61.

8.2.3 Trends in adoption of trawl vessel gears and technology

The information on vessel configurations, gears and technologies used by fishers was provided in the ‘stock status updates.mdb’ data file and the ‘Scallop raw data to send Nadia.mdb’ data file. This information was generated from past surveys and logbook gear sheets. Overall the otter-trawl vessel configurations for gears and technologies for saucer scallops covered 336 distinct boats from 1988–2016.

8.2.3.1 Vessel Configurations

Engine Power (Figure 8-2)

The average engine horse power increased by about 100 HP between 1988 and 2016.

Trawling Speed (Figure 8-2)

Only minor increases in trawling speed were detected. Average trawling speeds were faster at about 2.6 knots in 2016 compared with 2.3 knots in 1988.

Nozzles (Figure 8-2)

The proportion of annual fishing effort by vessels with nozzles increased by 50% between 1988 and 2016.

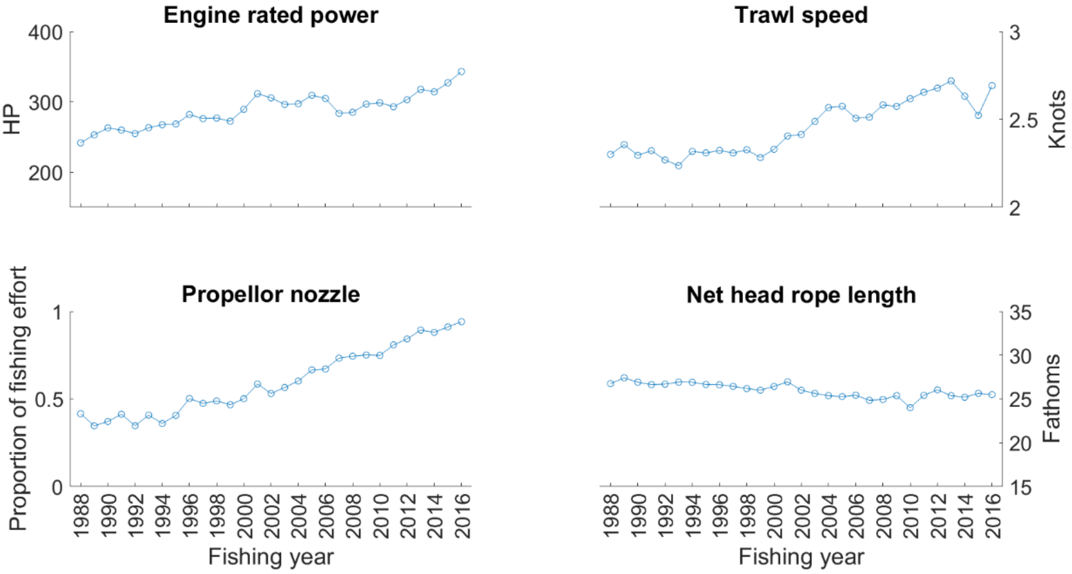

Figure 8-2 The average engine rated power, trawling speed, use of propeller nozzles and net size by fishing year. The averages were weighted according to the number of days fished by each vessel in each fishing year.

8.2.3.2 Net Configurations

Net types (Figure 8-3)

The configuration of nets used in the scallop fishery changed markedly over time. Essentially all vessels towed triple gear in 1988, and until 2007 more than half of the vessels towed triple gear. Since then there was a trend for more vessels to tow quad gear, and by 2016 82% of total fishing effort used quad gear. The proportion of vessels towing single, twin or five nets has remained negligible.

Net sizes (Figure 8-2)

The trends in the change in average net length used in all trawl sectors are influenced by the regulations. For the scallop fishery, the average total head rope length decreased slightly between 1988 and 2016.

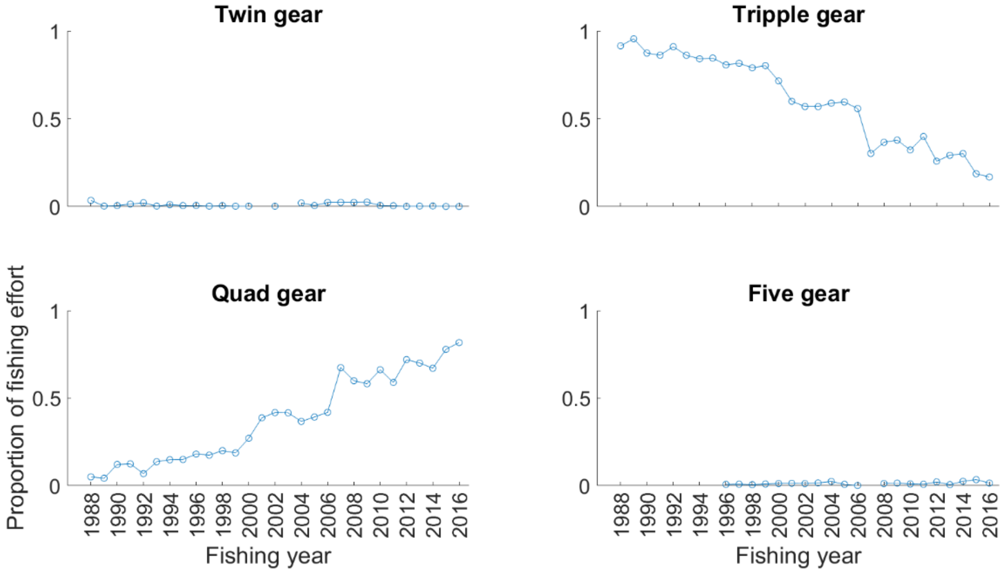

Figure 8-3 The proportion of total annual fishing effort by vessels using different net configurations.

Ground gear types (Figure 8-4)

Standard drop chains and their variants were the most commonly used ground gear.

Otter boards (Figure 8-5)

Pre-2004 flat otter boards were the most popular board type used across all trawl sectors. However, even during this period their use declined considerably. Over the same period there was an increase in the adoption of Kilfoil or Louvre boards. After 2004 the declining use of flat otter boards continued and in 2016 the percentage of effort with flat boards was 23%. 64% of total fishing effort was associated with Kilfoil or Louvre boards by 2016.

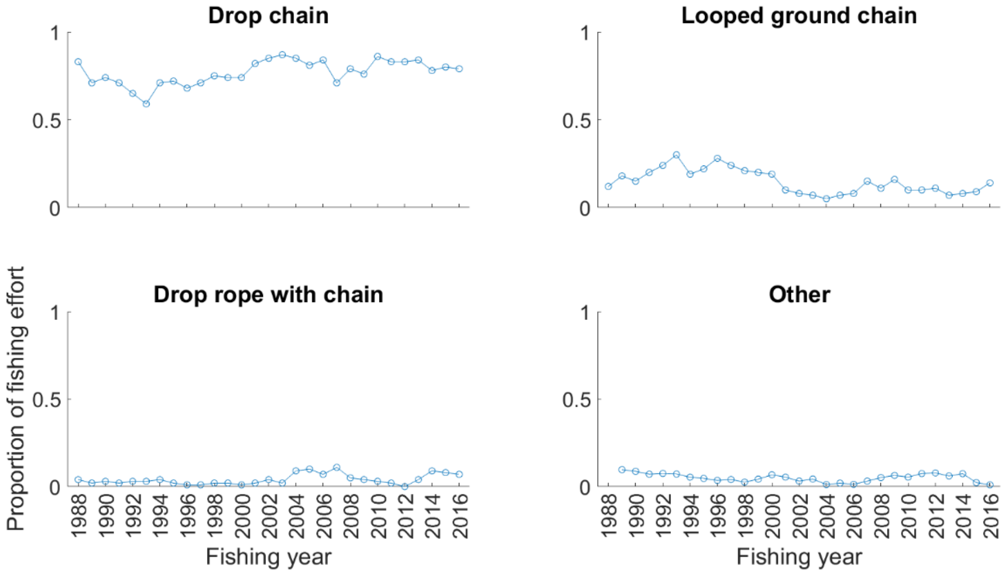

Figure 8-4 The proportion of total annual fishing effort by vessels in each fishing year using different ground gear.

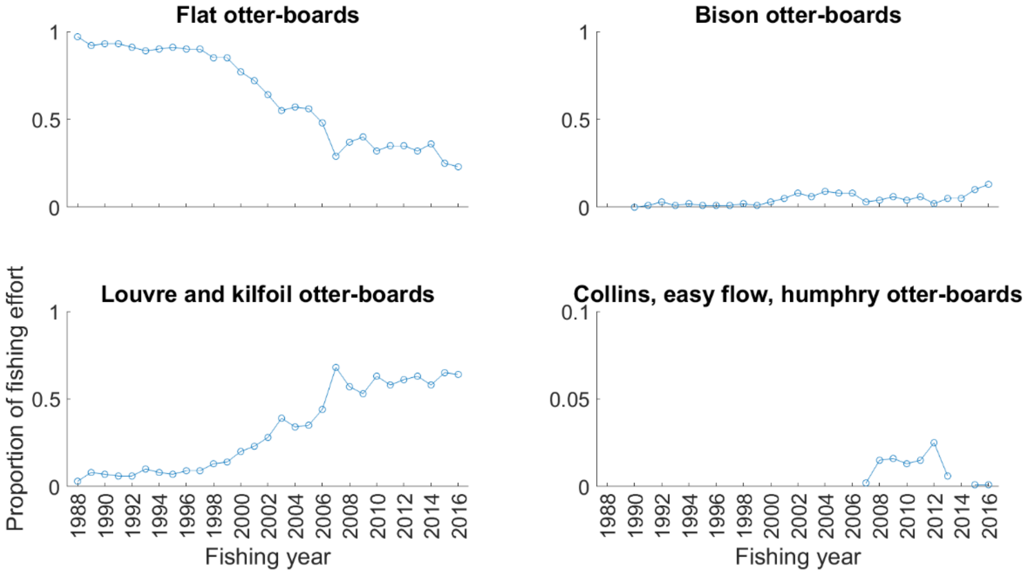

Figure 8-5 The proportion of total annual fishing effort by vessels in each fishing year using different otter boards.

8.2.3.3 Try gear, bycatch reduction devices and turtle excluders

Try gear (Figure 8-6)

Try gear is a small net (1-3 fathom head rope length) used by fishers for short, frequent (10-20 minute) sampling of trawl grounds. Since 1999 there has been a steady increase in its use and by 2001 it was used in 87% of total fishing effort.

Bycatch reduction devices (BRD) and turtle excluder devices (TED) (Figure 8-6)

TEDs and BRDs were trialled voluntarily in the Queensland east coast otter trawl fishery in the mid- to late-1990s and progressively made mandatory in different sectors between 1999 and 2002. TEDs and BRDs were made mandatory in the scallop sector on 1 July 2001.

8.2.3.4 Navigation and searching technologies

Sonar (Figure 8-6)

The adoption and use of sonar has generally remained low at less than 20%. (Note that sonar is generally used to detect objects that may pose a hazard to bottom trawling, and should not be confused with sounders which are universally adopted by the fleet to measure depth.)

Global Positioning System (GPS) (Figure 8-6)

GPS was rapidly adopted by fishers in the 1990s and is used by almost all vessels. GPS offered fishers improved spatial accuracy for trawling, with a precision of ≤ 50m.

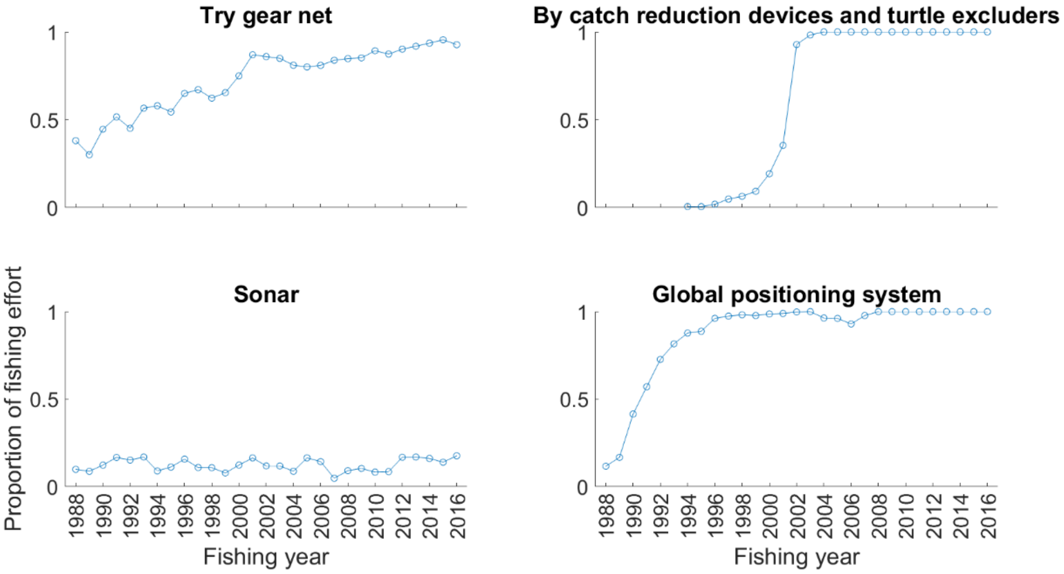

Figure 8-6 The proportion of total annual fishing effort by vessels in each fishing year using a try net, TEDs and BRDs, sonar and global positioning systems.

8.2.4 Analysis of scallop catches

8.2.4.1 Analysis of scallop catches 1988–2016

Table 8-8 contains the regression parameter estimates for the various gears and technologies based on the REML model for 1988–2016, treating vessel identifiers and grids as random effects (section 8.4.4 page 56 and equation 8-1 page 33) and fishing year, fishing month, log(hours), log(HP), sonar, GPS, net type, and ground gear as fixed terms.

Table 8-7 Linear mixed model (REML) analysis of saucer scallop catches from 1988–2016

Model description: section 8.2.2.1; Goodness of fit plots: section 8.4.4, Figure 8-16 page 58				
Estimated variance components (s.e.)				
Boat_mark	0.1098	0.0096		
Grid	0.0402	0.0147		
Residual variance (s.e.)	0.498 (0.0020)			
Fixed term	*Wald statistic*	*d.f. (degrees of freedom)*	*Wald/d.f.*	*Chi-square probability*
Fishyear.fishingmonth	9738.28	292	33.35	<0.001
Log(hours)	15516.78	1	15516.78	<0.001
Log(HP)	503.54	1	503.54	<0.001
Sonar	362.35	1	362.35	<0.001
GPS	4.86	1	4.86	0.028
Net type	134.41	3	44.80	<0.001
Ground gear	312.06	3	104.02	<0.001

The parameter estimate for sonar (Table 8-8) indicated that it was associated with an approximate average 25% increase in catches compared to vessels without the device. Similarly, vessels with a GPS were associated with approximately 3% higher catch rates. Drop chains were the most popular ground gear type used. The parameter estimates showed that using looped ground chain was associated with an approximate 0.1% increase in catches compared to vessels using drop chains. Smaller catches of scallops were associated with drop rope and other ground gears. Although there was a shift to quad gear since 2007 (Figure 8-7), the parameter estimates showed that vessels that towed triple gear had a 10% increase in average catch compared to vessels that towed quad gear. Triple gear allowed for the use of larger nets that were trawled at slower speeds (Figure 8-7). Vessels towing quad gear towed at a faster speed with slightly smaller nets than the nets towed in triple gear (Figure 8-7).

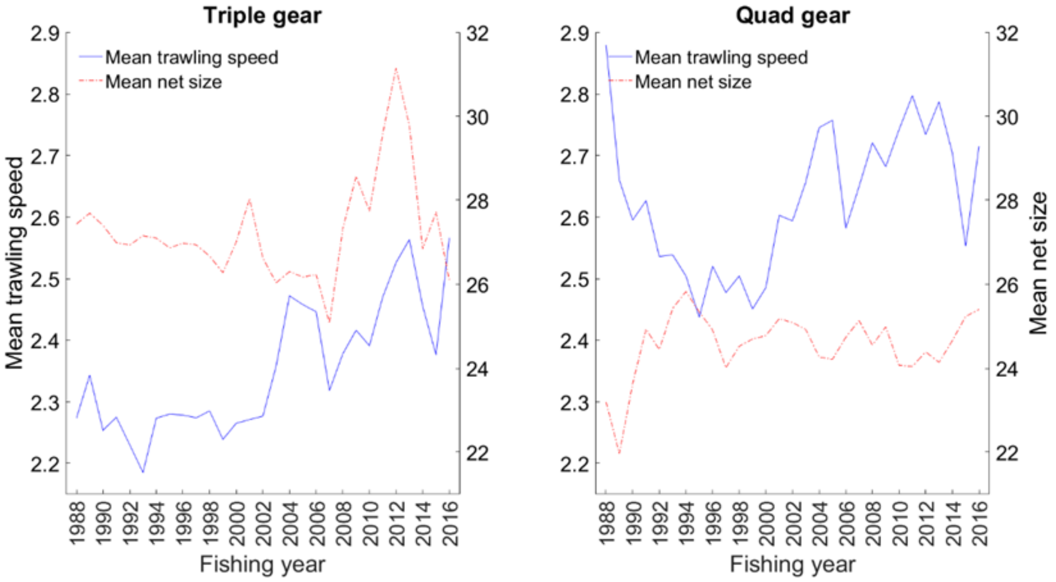

Figure 8-7 Interaction plots for triple gear and quad gear for net size and trawling speed. Triple gear allowed for the use of larger nets, trawled at slower speeds. Vessels towing quad gear towed at a faster speed with smaller nets.

Table 8-8 Untransformed (i.e. logarithm) parameter estimates β_2 and standard errors in parenthesis from the REML model based on the 1988–2016 time series; n.s. indicates the parameter was not significant and excluded from the analysis; h.c. indicates the data were correlated with other variables in the model and excluded from the analysis. Note that these are the parameter values in equation 8-1on page 33.

Parameter estimates β_2	**REML**
Log(HP)	0.45063 (0.01985)
Sonar	0.21972 (0.01150)
GPS	0.02754 (0.012152)
Trawl gear – number of nets	
Twin	0 (0)
Triple	0.21499 (0.0359)
Quad	0.11885 (0.0367)
Five	0.11219 (0.0605)
Ground Gear	
Drop chain	0 (0)
Looped ground chain	0.00106 (0.00997)
Drop chain and rope	-0.01454 (0.01467)
Other	-0.30312 (0.01702)
Trawl speed	n.s.
Propeller nozzle	h.c.
Otter boards	h.c.
Net size	h.c.
BRD and TED	h.c.
Lunar	n.s.
Lunar advanced	n.s.

There was no evidence of any influential correlations between gear and technology parameters (Table 8-21 page 57). As in Bishop *et al.* (2008) there was little effect of removing any of the correlations greater than 0.3 from the analysis, and the inferences on the remaining parameters remained unchanged.

For the statistical analysis the use of lognormal errors was appropriate (section 8.4.4, Figure 8-16 page 58). The histogram of standardised residuals was a symmetric bell-shape evenly distributed around zero, indicating a normal distribution is likely to be true. The scatter plot of standardised residuals against predicted values was symmetrically distributed and clustered towards the middle of the plot, indicating a normal distribution. There was a slight trend in residuals for negative values of log (predicted catches), which corresponds to daily catches of less than one basket. There were fewer than 1.5% of records with catches less than 1 basket. The normality plot also indicated that the log-transformed data were approximately normally distributed.

8.2.4.2 Analysis of scallop catches 1977–2016

The effects of gear and technology were included in the linear mixed model for 1977–2016 by adjusting $\log_e(C_{ivaym})$, as defined in equation 8-4. The GenStat code is given in section 8.4.6 and Table 8-26 on page 62. The offset parameters (Table 8-26 on page 62) used for this exercise were extracted from the parameter estimates for HP, sonar, GPS, net type and ground gear from the REML model 1988–2016 in Table 8-8.

The calculated fishing power offsets for the REML model relative to 1989 are shown in Figure 8-8. The highest median occurs in 2001.

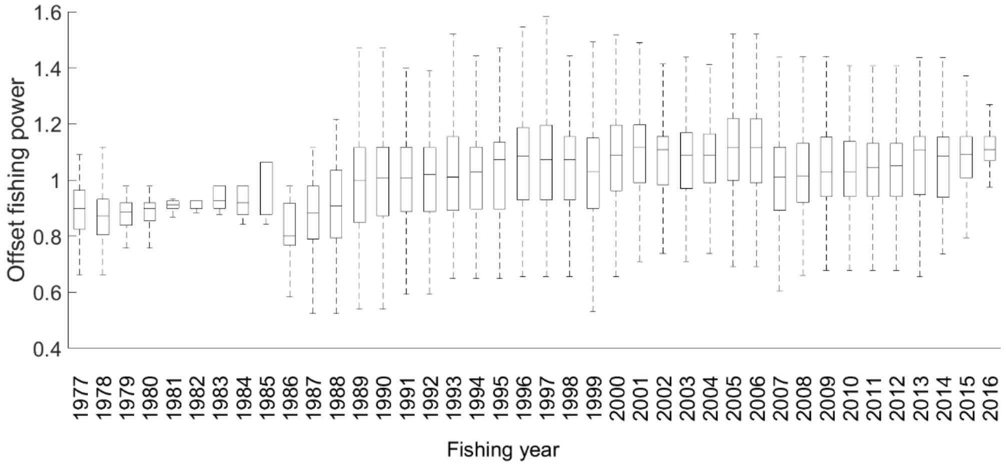

Figure 8-8 Calculated fishing power offsets for the REML model for the 1977–2016 data relative to 1989. Offsets were calculated using the parameter estimates from the REML model 1988–2016.

Table 8-9 REML model analysis of saucer scallop catch rates from 1977 to 2016.

Model description: Section 8.2.2.2 page 34, Goodness of fit plots: section 8.4.6, Figure 8-18 page 63				
Estimated variance components (s.e.)				
Boat_mark	0.1005	0.0077		
grid	0.0400	0.0146		
Residual variance (s.e.)	0.489 (0.0019)			
Fixed term	*Wald statistic*	*d.f. (degrees of freedom)*	*Wald/d.f.*	*Chi-square probability*
Fishyear.fishingmonth	11220.40	409	27.43	<0.001
Loghours2	21448.82	1	21448.82	<0.001

8.3 Results and Discussion

8.3.1 Estimates of fishing power

8.3.1.1 Fishing power 1988–2016

The REML model measured annual changes in fishing power based on fixed and random components. Gear changes, technology upgrades and hours-fished were considered as fixed terms in the model for the catchability estimates β_2. For the fixed terms, the variability in fishing power is represented by the dotted line in Figure 8-9. Changes in fishing power due to fleet profile were measured by treating individual vessels as random terms (γ, see section 8.2.2 page 33). These changes in fishing power are illustrated by the difference between the overall fishing power estimate (solid line) and the estimate from the β_2 fixed effects (dotted line). The 1989 fishing year was selected as the base reference as it was the first fishing year with complete catch records across all sectors and is consistent with O'Neill and Leigh (2006).

Fishing power increased by 15% between the 1989 and 2016 fishing years, based on the REML (Figure 8-9, including fixed and random catchability terms). If only fixed catchability terms were considered, then fishing power increased by about 20% over this period. This was driven by increases associated with vessels having higher HP, increased use of GPS and sonar, and the type of trawl gear. Fishing power was driven by more efficient vessels (measured by the vessel parameters and compared to the 1989 fleet; i.e. blue solid line is above the dotted red) rather than gear and technology effects for the fishing years 1990-1999 and 2006-2010. The fishing years 1988, 2003, 2011 and 2015-2016 showed that overall fishing power was down due to more efficient vessels (i.e. vessels with higher parameters estimates) fishing less in these years (blue solid line is below the dotted red). In Figure 8-9 the lines of the overall fishing power (solid line) and fishing power due to fixed terms-only (dotted line) intersected in the fishing years 1989, 2000-2002, 2004-2005, 2011-

2014, indicating in these years that the fleet of vessels operating had similar vessel-parameters to the 1989 fleet.

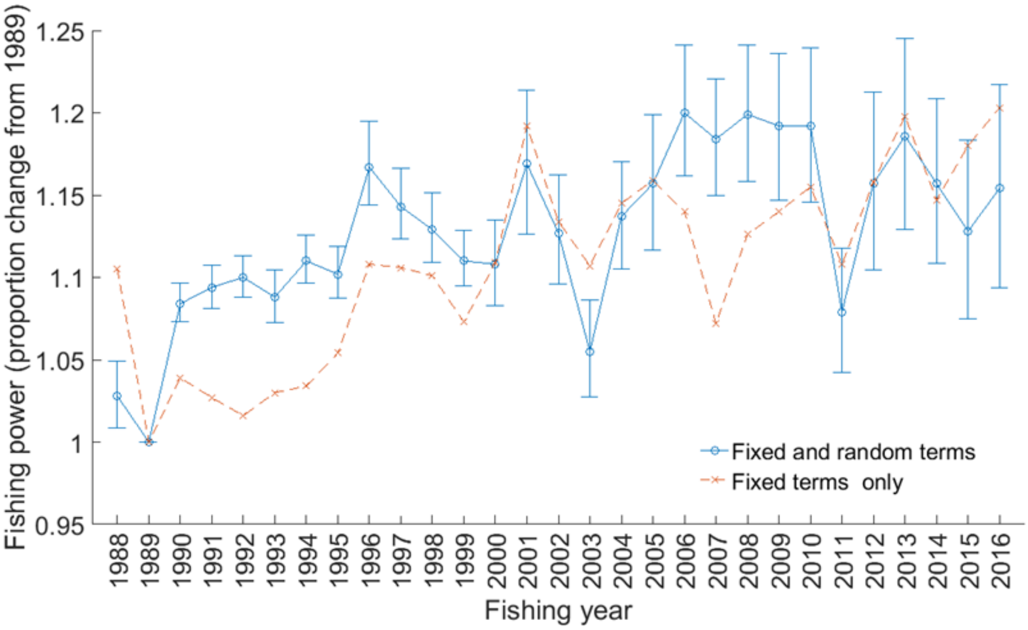

Figure 8-9 Annual fishing power trends for saucer scallops as calculated from the REML model. The changes represent the difference from the 1989 base reference fishing year, which was set at one. Error bars illustrate the 95% confidence intervals.

8.3.1.2 **Fishing power 1977–2016**

Average fishing power increased by 16% from the 1989 to 2016 fishing years (Figure 8-10); similar to the data and result in Figure 8-9. Pre-1989 the general trend of increasing fishing power was associated with estimated increases in vessel engine HP (Figure 8-17 on page 61). From 1977 to 1989 fishing power was estimated to have increased by about 20–25%. From 1977 to 2016 estimated increases in fishing power were about 40–50%.

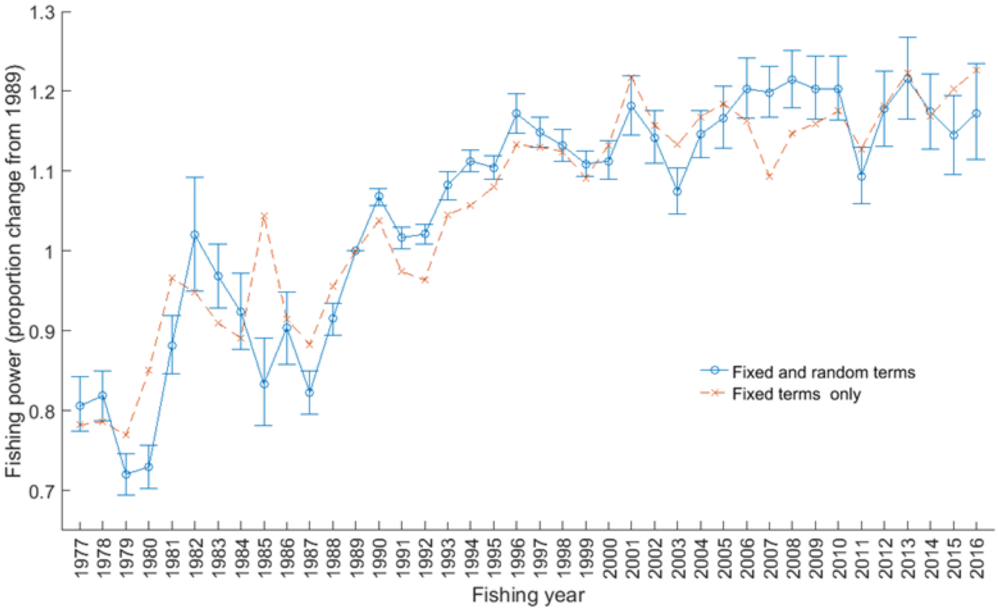

Figure 8-10 Annual fishing power trends for saucer scallops as calculated from the REML model. The change represents the difference from the 1989 base reference year, which was set at one. Error bars illustrate the 95% confidence intervals.

8.3.2 Standardised catch rates

8.3.2.1 Standardised catch rates 1988–2016

For the standardised catch rate predictions values of the variables in the fixed terms were set as outlined in Table 8-10. GenStat code for the predictions is in section 8.4.4 and Table 8-22 on page 59.

Boat mark 331 was selected in the predictions. A box-plot of all boat mark effects by fishing year showed that on average, the greatest effect on catches due to the random vessel term occurred in 2007, with an effect of 0.13160. Thus a vessel with a parameter value closest to 0.13160 was selected in order to set the vessel term to a vessel that resulted in the largest effect on the number of scallop baskets.

Monthly standardised catch rates showed a general decline from 1988–1997, remained relatively stable from 1998–2006, and generally increased from 2007–2013 (Figure 8-11). Catch rates exceeded 27 baskets boat-day^{-1} in November 2013 and declined thereafter. These relatively high catch rates were observed in several grids throughout the fishery (see Figure 8-12 and Figure 8-13 below). From January 2015 to April 2016 monthly standardised catch rates averaged 7 baskets boat-day^{-1}. In a number of fishing years, the within year declines (depletions) in catch rates were quite marked.

Table 8-10 Set values of fixed terms in the REML for predicting standardised catch rates 1988–2016.

Term	Set to	Reason
Ground gear	Drop chain	Most popular ground gear
Net type	Quad gear	Since 2007 there has been a shift to the adoption of quad gear
GPS	Using GPS	GPS has been fully adopted and used by almost all vessels since the late 1990s
Sonar	Using sonar	It is unclear if the use of sonar improved catches, but sonar is associated with vessels with higher catches
Log(hours)	2.508	Based on the estimated mean of hours-fished between 2007–2016, which back-transforms to 12.28 hours.
Log(HP)	5.822	Yearly estimate of 2016 log(HP) relative fishing power. This is equivalent to 338 HP.

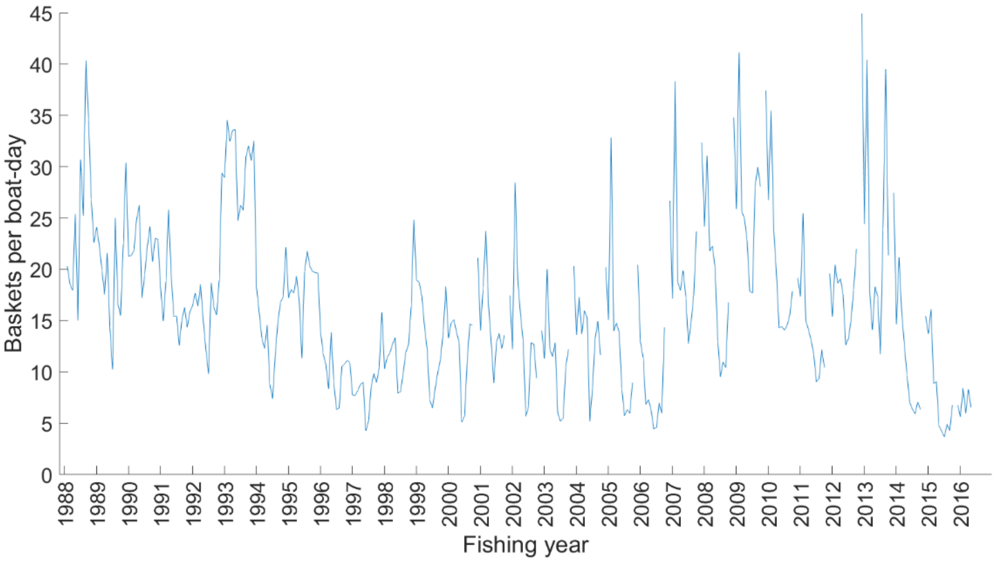

Figure 8-11 Mean monthly standardised catch rates of saucer scallops from 1988-2016. The x-axis tick marks indicate November which is the start of the fishing year. Breaks in the time series after 2000 represent the southern temporal closure which occurs from 20 September to 1 November annually. For comparing means, the 95% lower and upper confidence interval on catch rates generally ranged ± 3 baskets with a maximum of 10 baskets in April 1989.

Annual standardised catch rates have declined in recent years (i.e. 2014–2016) in nearly all fishing grids (Figure 8-12 and Figure 8-13). Catch rates in grids S28, T30 and V32 (Rockhampton to Hervey Bay), which include the scallop rotational closures, were relatively stable from 1990–2013, but thereafter declined (Figure 8-12). Catch rates for the three most-southern grids W33, W34 and W35 (Fraser Island to Noosa) were highly variable from 1989–2013, but showed a general increasing trend over this time period, thereafter declining from 2014–2016 (Figure 8-13).

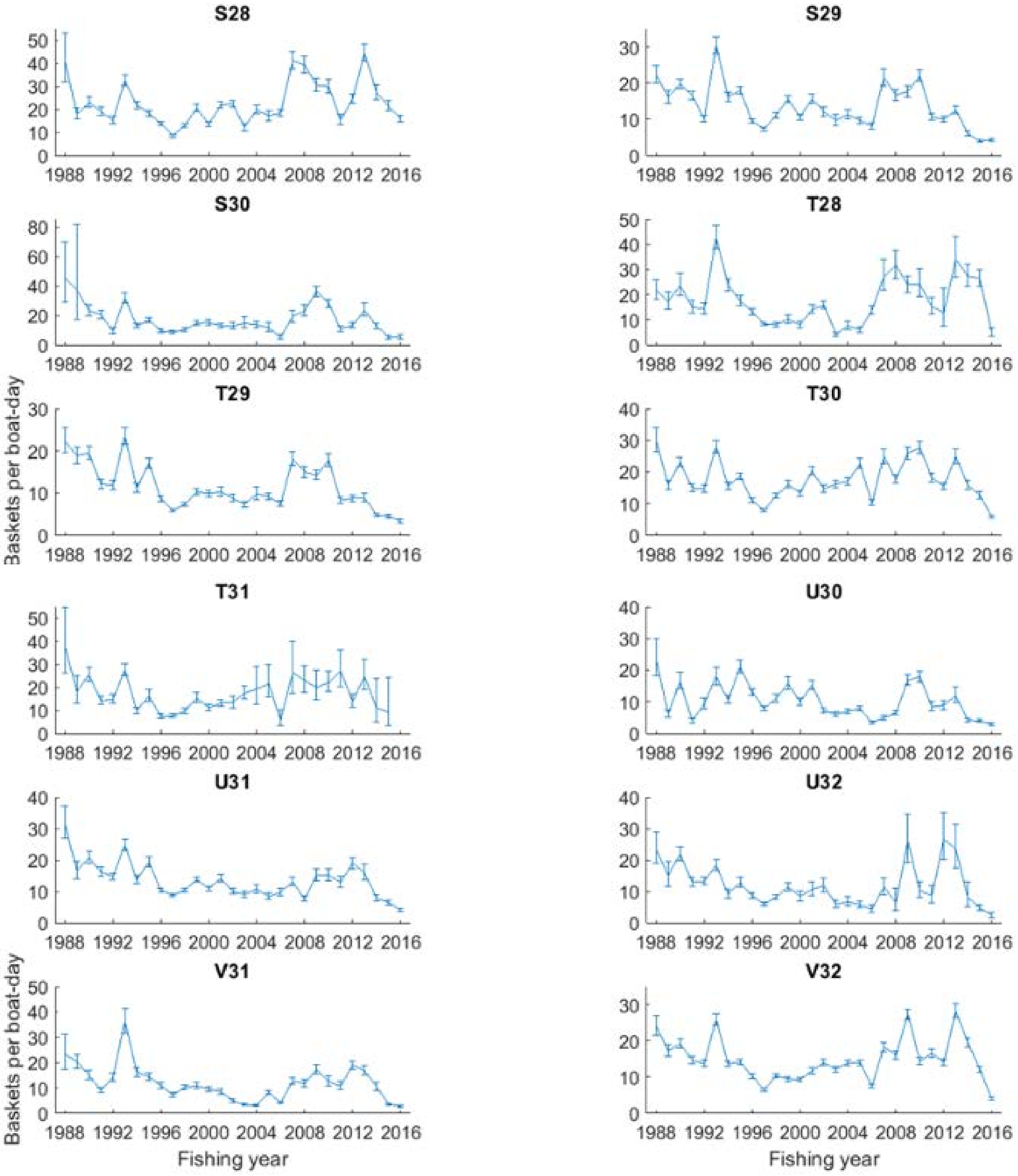

Figure 8-12 Average standardised annual catch rates of saucer scallops from each 30 x 30 minute CFISH grid between Rockhampton and Hervey Bay.

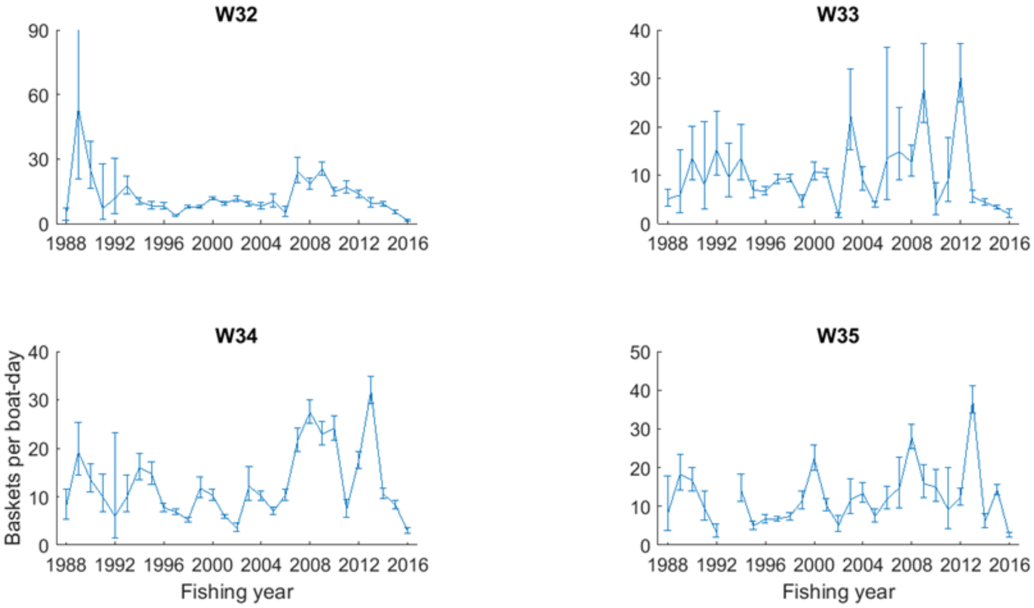

Figure 8-13 Average standardised annual catch rates of saucer scallops from each 30 x 30 minute CFISH grid from east of Fraser Island and south to Noosa in southern Queensland.

8.3.2.2 Standardised catch rates 1977–2016

For the catch rate estimations, values of the variables for the fixed terms (Table 8-26 page 62), namely log(hours), were set according to the value used for log(hours) in the REML catch rate predictions 1988–2016 (Table 8-10). Thus log(hours) = 2.508. GenStat code for the predictions is provided in section 8.4.6 Table 8-28 page 64.

Boat mark 367 was selected in the predictions. An analysis of the boat mark effects showed that on average, the greatest effect due to the random vessel term was in 2007, with a parameter of 0.16011. Thus a vessel with a parameter value closest to 0.16011 was selected in order to set the vessel term to a vessel that resulted in the biggest effect. This vessel was not the same vessel that was selected for the 1988–2016 dataset predictions. However, the parameter estimate from the linear mixed model 1977–2016 for the vessel selected for the 1988–2016 catch rate standardisation was 0.14735, and therefore very close to 0.16011.

The long-term trend in predicted catch rates is marked by a strong decline between pre-1988 and post-1988 (Figure 8-14). Predicted catch rates were relatively high from 1977–1987, and declined from 1979–1982 and 1984–1988. The highest catch rate exceeded 200 baskets boat-day^{-1} in July 1983, although this is based on few observations (Table 8-11). Standardised catch rates exceeded 150 baskets boat-day^{-1} in June 1977 and October 1979, and frequently exceeded 50 baskets boat-day^{-1} from 1982–1985. In contrast, from January 2015 to April 2016, monthly standardised catch rates averaged 5 baskets boat-day^{-1}.

The overall long-term trend should be interpreted with caution, particularly in regard to the relatively high catch rates from 1977–1987, when scallop management measures for MLS, net size and daily hours-fished were generally less conservative compared to post-1988 (see Table 8-2 for details).

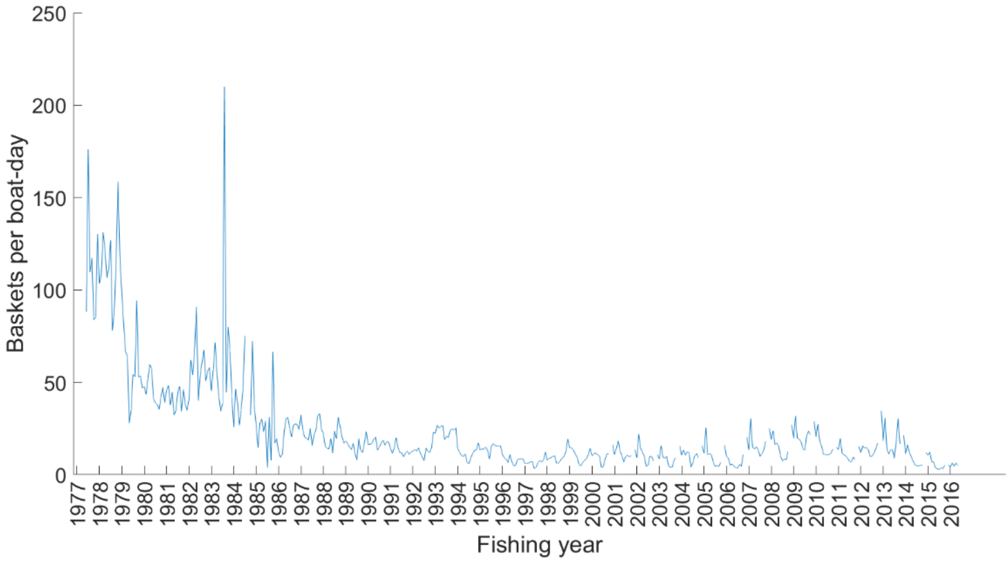

Figure 8-14 Mean monthly standardised catch rates of saucer scallops between 1977 and 2016. The effects of fishing power were included by adjusting means using the linear predictors from REML 1988–2016 for HP (0.45063), sonar (0.21972), GPS (0.02754), net type (0.21499 for triple gear, 0.11885 for quad gear, 0.11219 for five gear), and ground gear (0.00106 for drop chain, -0.01454 for looped ground chain, and -0.30312 for drop rope with chain. The x-axis tick marks indicate November which is the start of the fishing year. For comparing means, the 95% confidence interval generally ranged by ± 23–42 baskets pre-1988 and 5–8 baskets thereafter. Note the large spike in July 1983 was based on only 3 boat-days of fishing (for sample sizes see Table 8-27).

8.4 Fishing power procedures and command files

8.4.1 Selection process for eleven individual vessels from HTRAWL

From ‘glmdata.gsh’, counts of days-fished per year were tabulated for each vessel from the historic HTRAWL data. For calendar years 1977–1987, there were 205 different vessels that participated in supplying historic logbook information that were selected as part of the catch rate standardisations in FRDC Project No. 2006/024 (Campbell *et al.* 2010). It should be noted that there were varying amounts of data for each calendar year (Table 8-11). 1982–1985 (inclusive) had small sample sizes in terms of number of participating vessels (i.e. 6 or fewer) and days-fished per year (i.e. 273, 212, 134, 217, respectively). The number of baskets of scallops caught was also lower in these years, especially in 1985. The possible impacts of small sample sizes on the catch standardisation should be considered.

Table 8-11. Summary of historic scallop catch and effort within ‘glmdata.gsh’.

Calendar year	Number of vessels Participating	Number of days fished	Mean days fished per participating vessel	Number of baskets caught
1977	40	780	20	59 811
1978	51	1436	58	116 870
1979	43	769	18	30 661
1980	44	1191	27	33 814
1981	18	293	16	9 852
1982	5	273	55	11 806
1983	5	212	42	9 110
1984	6	134	22	4 165
1985	4	127	32	2 233
1986	19	718	38	11 507
1987	124	3631	29	68 106
Total	205	9561	Mean=32	357 935

No vessel in the ‘glmdata.gsh’ table provided data continuously between 1977 and 1987. However, 22 vessels were identified as having more than 10 days of fishing effort per calendar year in several years between 1977 and 1987 as well as in several years after 1988. The 22 vessels had more than 10 days per year for several years in both the HTRAWL and CFISH data series.

Of these 22 vessels, 11 were selected for further investigation of their catch data and catch rates over time. These 11 vessels were considered to have a reasonable number of days of fishing in both the HTRAWL and CFISH data sets as well as reasonable catches of scallops.

The data in ‘glmdata.gsh’ for each of the 11 vessels were checked against data in ‘Htrawl2000.mdb’. To do so required identifying the boat record number (BRN) for each vessel and tracking data for each vessel over time. It was assumed that vessels were correctly matched with their respective BRNs in the work completed previously for FRDC Project No 1999/120.

The standardised average monthly catch rates per boat-day for the 11 vessels declined markedly from 1977–2007 (Figure 9-15). This suggests the decline observed using all vessels (i.e. Figure 8-14) was not due to changes in the fishing power or reporting procedures of vessels contributing to the early pre-1988 HTRAWL data compared to those contributing to the post-1987 CFISH data.

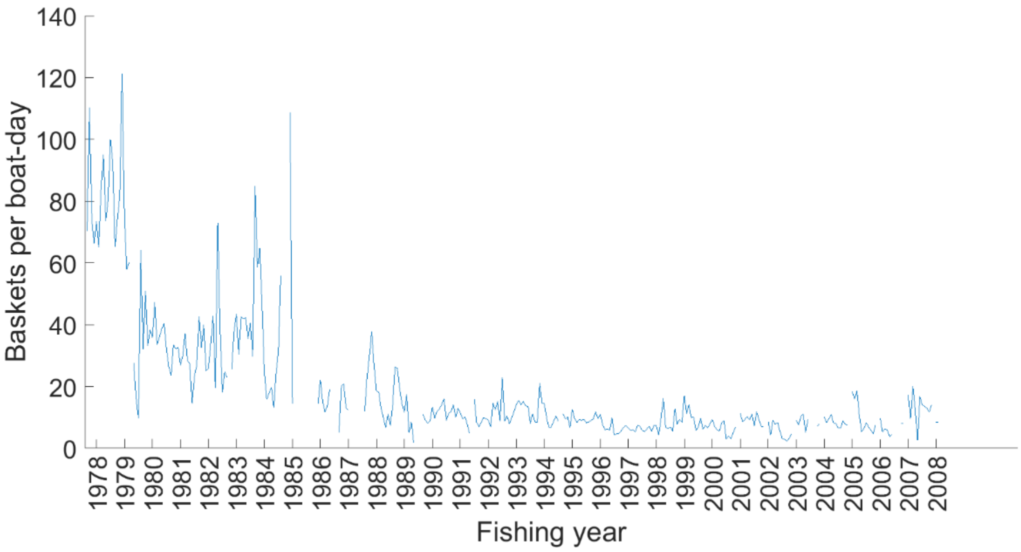

Figure 8-15 Standardised mean monthly catch rates for the 11 vessels that provided catch rate data prior to, and after 1988 when the mandatory logbook database program was implemented. The catch rates were standardised generically to the average fishing power of the 11 vessels; which is a different to the fishing power scale standardised in other analyses. Note the x-axis tick-marks indicate the month of November, which is the start of the fishing year.

8.4.2 Imputation model for missing hours

Table 8-12 Summary statistics for hours in CFISH (1988–2016)

Number of values	124 974
Number of missing values	8 754
Mean	12.36
Standard deviation	3.372

Table 8-13 Over dispersed Poisson model used for imputation of missing hours

```
MODEL [DISTRIBUTION=poisson; LINK=logarithm; DISPERSION=*] hours

FITINDIVIDUALLY [PRINT=model, deviance, summary, estimates; CONSTANT=estimate;
FPROB=yes;\

TPROB=yes; FACT=9;
selection=%variance,%ss,adjustedr2,r2,seobservations,dispersion,%meandeviance,%deviance,aic,
sic;]\

boat_mark+month+year+logn
```

The adjusted R-squared statistic is 0.241.

Table 8-14 Poisson model for imputation of hours in CFISH (1988–2016)

Fixed Term	**Wald statistic**	**d.f.**	**Wald statistic/d.f.**	**Chi square probability**
boat_mark	13102	332	39.46	<0.001
Month	580	11	52.71	<0.001
Year	3948	28	140.99	<0.001
Logn	12848	1	12848.38	<0.001

Table 8-15 Summary statistics for imputed hours in CFISH (1988–2016)

Number of values	124 974
Number of missing values	0
Mean	12.40
Standard deviation	3.339

Table 8-16 Summary of hours in HTRAWL and CFISH (1977–2016)

Number of values	134 535
Number of missing values	8 754
Mean	12.32
Standard deviation	3.581

Table 8-17 Poisson model for imputation of hours in HTRAWL and CFISH (1977–2016)

Fixed Term	Wald statistic	d.f.	Wald statistic/d.f.	Chi square probability
boat_mark	13317	449	29.66	<0.001
Month	839	11	76.26	<0.001
Year	5621	39	144.12	<0.001
logn	17096	1	17 095.55	<0.001

Table 8-18 Summary statistics for imputed hours in HTRAWL and CFISH (1977–2016)

Number of values	134 535
Number of missing values	0
Mean	12.36
Standard deviation	3.542

8.4.3 REML command file for catch rate standardisation used in FRDC Project No 2006/024

Table 8-19 Example GenStat code used to analyse saucer scallop catches

```
VCOMPONENTS [FIXED= loghours_orig+fish_year*month+grid+logprawns+lunar+lunar_adv;\
FACTORIAL=2] RANDOM=boat_mark+boat_mark.fish_year;  INITIAL=1; CONSTRAINTS=positive
REML [PRINT=model,components,effects,deviance,waldTests,means; PSE=allestimates;
MVINCLUDE=*; method=ai;] logwt
```

8.4.4 REML command file, diagnostics and data summary 1988–2016

REML analysis allows for fixed and random model terms. Fixed effects are used to describe characteristics imposed where the effect of those specific choices is of interest. The fixed terms selected were fishing year, fishing month, log(hours-fished), log(HP), sonar, GPS, net type and ground gear. For example, the presence or absence of a GPS on board a vessel was treated as a fixed term to estimate whether catches improved when fishing with the device. The random effects are used to describe the effects of factors where the values present in the data can be considered as a random selection of values from the large population. The random terms selected were boat_mark and logbook grid.

Table 8-20 Example GenStat code used to analyse saucer scallop catches

```
‘Linear mixed model. REML’

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
```

Table 8-21 Linear correlations between some of the different saucer scallop vessel characteristics

	Logn	loghp	nozzle	nnets	sonar	gps2	tryyesno	brdted	lognet	logspeed
Logn	1.000									
Loghp	0.233	1.000								
nozzle	0.171	0.459	1.000							
Nnets	0.038	0.324	0.297	1.000						
Sonar	0.137	0.280	0.260	0.128	1.000					
gps2	-0.031	0.217	0.214	0.195	0.085	1.000				
tryyesno	0.152	0.528	0.437	0.369	0.146	0.252	1.000			
brdted	0.036	0.180	0.271	0.387	0.016	0.250	0.305	1.000		
lognet	0.168	0.431	0.120	-0.190	0.151	0.014	0.143	-0.108	1.000	
Logspeed	0.005	0.180	0.245	0.390	-0.041	0.155	0.126	0.324	-0.087	1.000

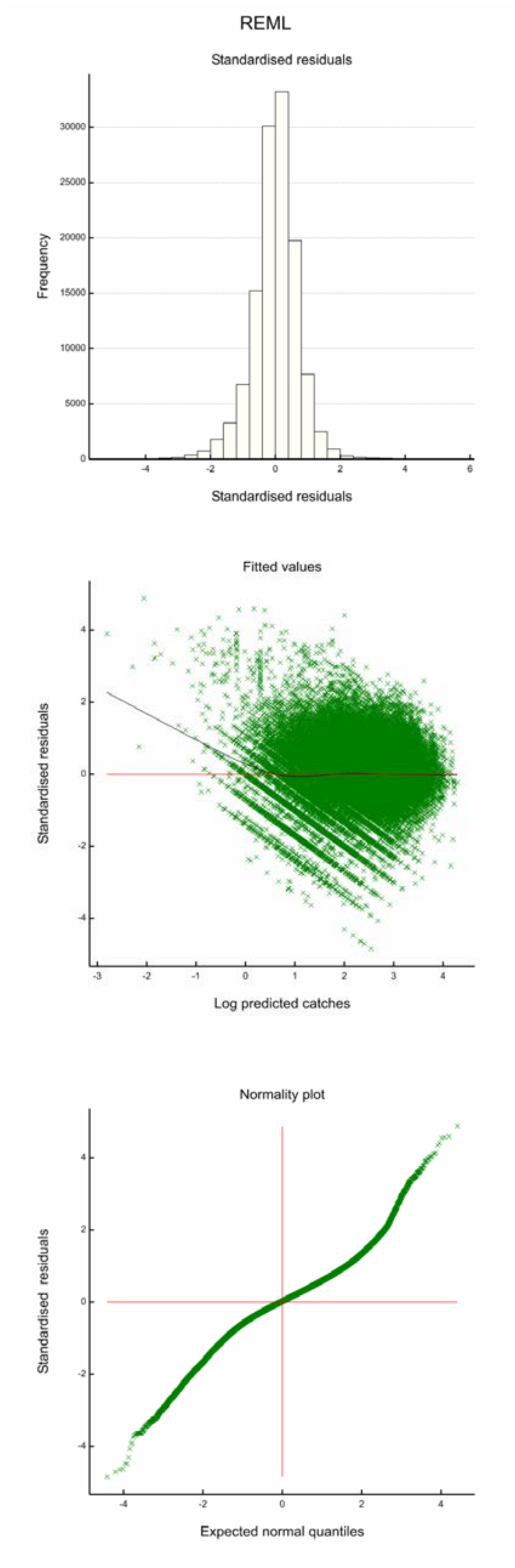

Figure 8-16 Standardised residuals from the saucer scallop analyses.

Table 8-22 Example GenStat code used to predict saucer scallop standardised catch rates. The setting of the variables at the particular values is explained in 8.3.2.

```
vpredict [print=description,predictions,se; PRED=Lnormym; SE=LnormymSE]
fishyear,fishingmonth,\
ggear4,nettype,gps2,sonar,loghp,loghours2,boat_mark;\
levels=*,*,!(1),!(3),!(1),!(1),!(5.822),!(2.508),!(331)
```

Table 8-23 Yearly summary of vessels and daily catches of saucer scallops analysed. * *indicates incomplete years.*

Fishing year	Number of vessels	Number of days fished
1988 *	36	1003
1989	46	1497
1990	66	4610
1991	70	3256
1992	68	3181
1993	81	5185
1994	95	4459
1995	120	6845
1996	137	6681
1997	152	9343
1998	159	8214
1999	125	6224
2000	138	6398
2001	100	5334
2002	92	3935
2003	77	3153
2004	102	3500
2005	106	4046
2006	87	2835
2007	54	2585
2008	98	4027
2009	103	5107
2010	94	4025
2011	96	2724
2012	89	4726
2013	99	3259
2014	82	2880
2015	93	3573
2016*	78	2369

8.4.5 Imputation procedures for missing gear data 1977–2016

Procedures used to impute gear data for HTRAWL data used the 1977–1987 data in ‘revised glmdata.gsh’.

Table 8-24 Methods applied to impute sonar, GPS, net type and ground gear in HTRAWL data ‘revised glmdata.gsh’

Characteristic	Imputed value in HTRAWL
Sonar	0.123 (average of sonar in CFISH data)
GPS	0 (no GPS)
Net type	3 (triple gear)
Ground gear	1 (drop chain)

In order to impute HP, each vessel from HTRAWL was matched to the earliest vessel record in the *tbl fishers details table* in ‘Scallop raw data to send Nadia.mdb’. This join resulted in three scenarios listed in Table 8-25.

Table 8-25 Methods used to impute HP in HTRAWL data. Each vessel in HTRAWL was matched to the earliest vessel record in the tbl Fishers detail table in ‘Scallop raw data to send Nadia.mdb’, resulting in three scenarios listed below.

Scenario	**Number records in HTRAWL**	**Procedure**
HP recorded on *tbl fishers details table*	6150 out of 9561 rows (64%) 131 distinct boats	HP (HTRAWL) = MainEnginePower (*tbl fishers details table*)
HP not recorded on *tbl fishers details table* and length recorded on *tbl fishers details table*	684 out of 9561 rows (7%) 10 distinct boats	Length (HTRAWL) = Length (*tbl fishers details table*). A quadratic regression model using HP and length imputed missing engine power values with random variation for each vessel where there was a length value. The model code was fitglm(x,y,'quadratic','Distribution','poisson','DispersionFlag',true) where x is length and y is HP
HP and length not recorded on *tbl fishers details table*	2727 out of 9561 rows (29%) 64 distinct boats	A mean model using HP and length imputed missing engine power values with random variation for each vessel where there was no length or engine power value. The model code was: fitglm(x,y,'constant','Distribution','poisson','DispersionFlag',true) where x is length and y is HP

Figure 8-17 shows a box plot of the imputed engine rated power of daily boat catches 1977–2016 and indicated an increasing trend in engine rated power of vessels over time.

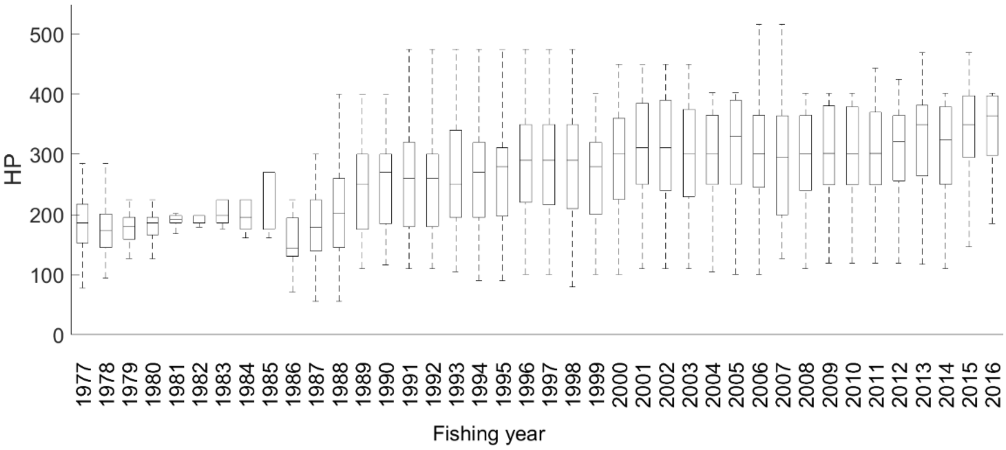

Figure 8-17 Box and whisker plot of the horse power of vessels from 1977–2016 after the imputation of missing gear data. The boxes show the variability about the medians for box-to-box comparison. The whiskers show the extent of the data. Note the increasing trend over time.

8.4.6 REML command file, diagnostics and data summary 1977–2016

The effects of fishing power were included by adjusting $\log_e(C_{ivaym})$ in equation 8-4 (Table 8-26, where n in the GenStat code is C from equation 8-4). The numbers written in the calculation of offsetlog in Table 8-26 were extracted from the linear predictors for HP, sonar, GPS, net type and ground gear from the REML model 1988–2016 in Table 8-20.

REML analysis includes fixed and random model terms. Fixed effects are used to describe characteristics imposed where the effect of those specific choices are of interest. The fixed terms selected were fishing year, fishing month and log(hours). For example, the effects of hours-fished on catch rate were investigated by selecting log(hours) as a fixed term. The random effects are used to describe the effects of factors where the values present in the data can be considered as a random selection of values from the large population. The random terms selected were boat_mark and grid. For example, an individual vessel from the entire trawl fleet was a possible random selection from total number of vessels.

Table 8-26 Example GenStat code used to analyse saucer scallops

```
calculate offsetlog = loghp*0.45063+sonar*0.21972+gps2*0.02754+\
(nettype.eq.3)*0.21499+(nettype.eq.4)*0.11885+(nettype.eq.5)*0.11219+\
(ggear4.eq.3)*0.00106+(ggear4.eq.4)*-0.01454+(ggear4.eq.5)*-0.30312

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
```

Table 8-27 Yearly summary of the number of vessels and daily catches of saucer scallops recorded through the HTrawl logbooks.

Fishing year	Number of vessels	Number of days fished
1977	40	780
1978	51	1436
1979	43	769
1980	44	1191
1981	18	293
1982	5	273
1983	5	212
1984	6	134
1985	4	127
1986	19	718
1987	124	3631

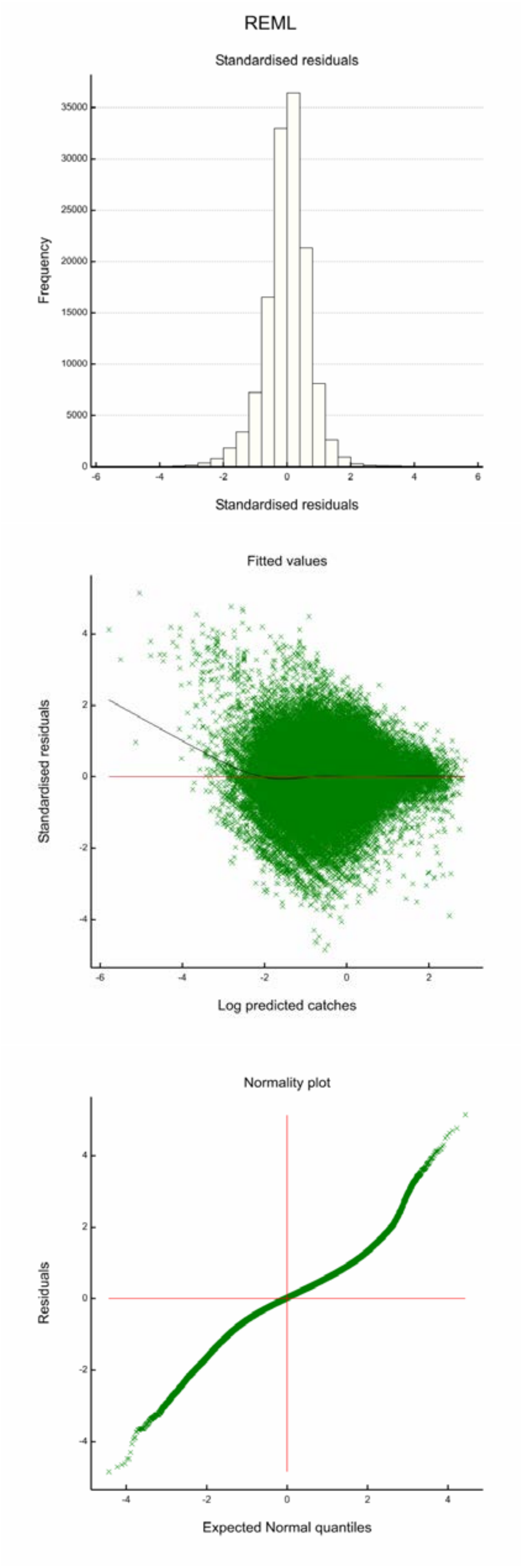

Figure 8-18 Standardised residuals from the pre-1988 saucer scallop analysis.

Table 8-28 Example GenStat code used to predict standardised scallop catch rates

```
vpredict [print=description,predictions,se; PRED=Lnormym; SE=LnormymSE]
fishyear,fishingmonth,\
loghours2,boat_mark;\

levels=*,*,!(2.508),!(367)
```

9 Appendix 2 - Scallop stock assessment

This section of the report refers to the data, population dynamics and outputs of the stock assessment.

9.1 Data for stock assessment

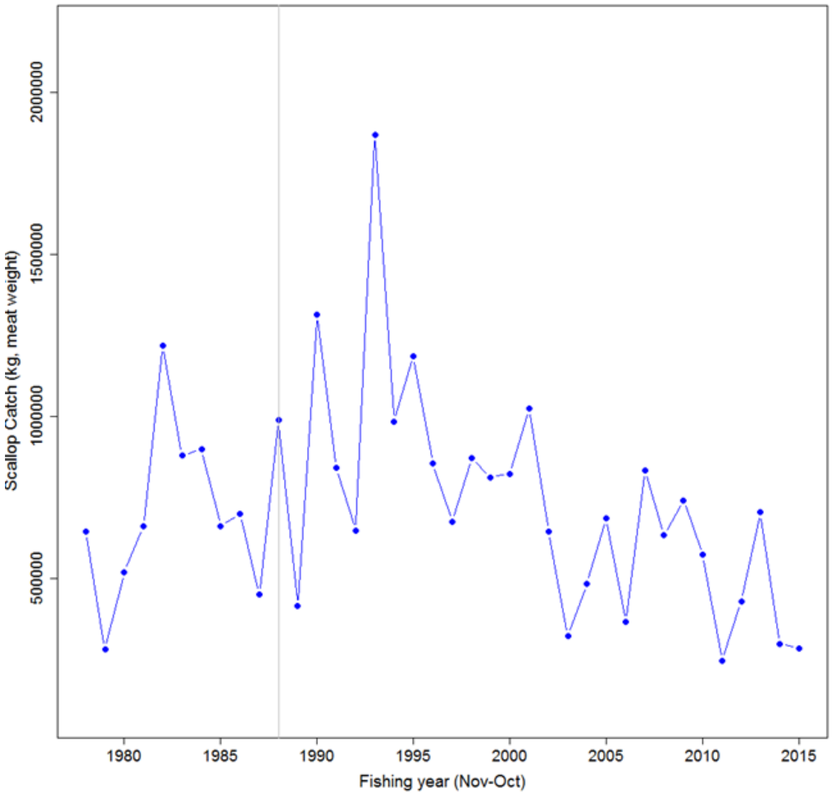

Figure 9-1 The time series of total annual catch from 1978 to 2015 fishing years. The grey vertical line refers to the 1988 fishing year. The total annual catch from 1978 to 1988 is based on data provided by Dredge et al. (2016). The post-1988 total annual catch is from CFISH. The historical data were only available for whole calendar years (Jan–Dec) but were treated as fishing years (Nov–Oct) in the stock assessment model.

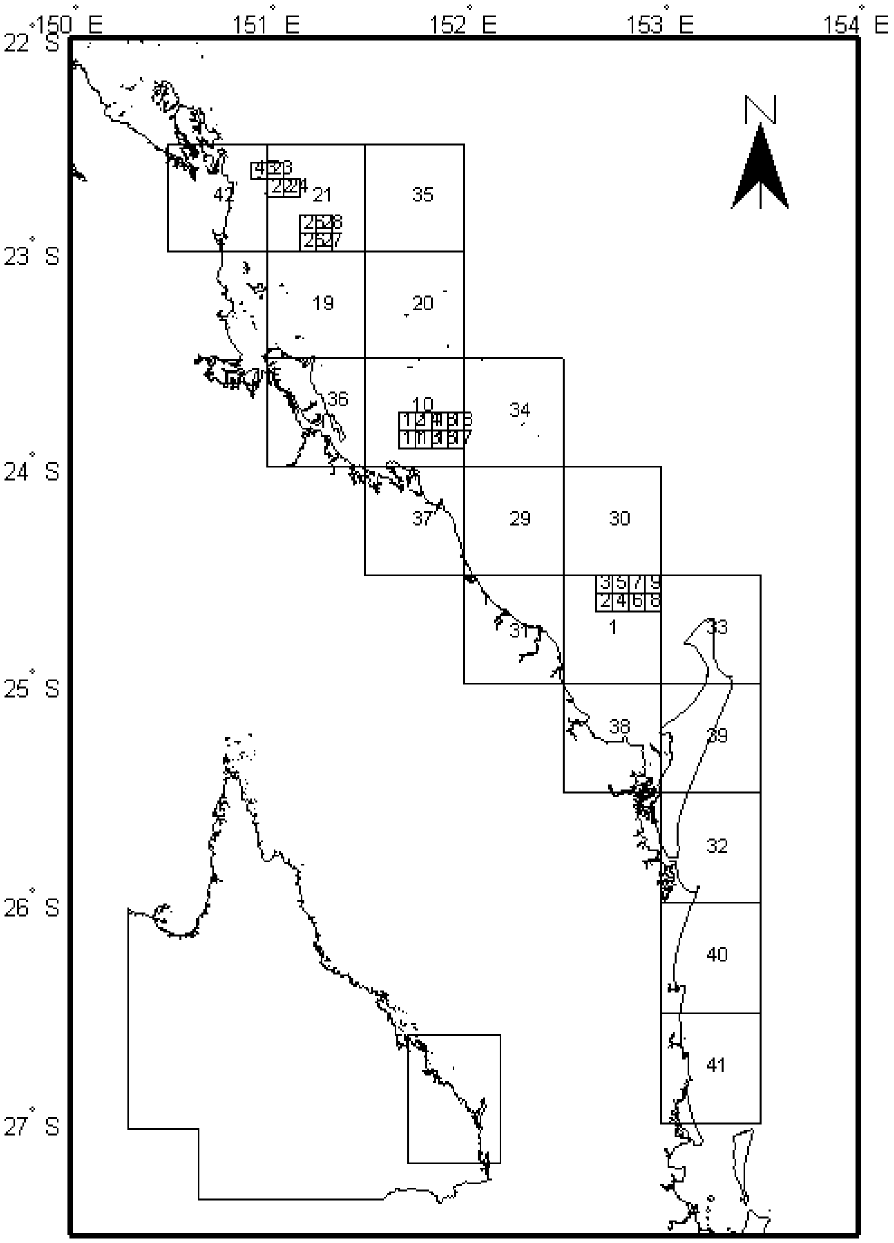

Figure 9-2 The 30 x 30 and 5 x 5 minute latitudinal and longitudinal cells representing the Queensland saucer scallop fishery (Campbell et al. 2012). The 30 x 30 minute cells are the most commonly used spatial resolution in the CFISH data, and the coarsest. The 5 x 5 minute cells encompass the scallop replenishment areas. The total number of cells is 43. The area A_k of cell k was calculated based on the VMS effort data in a way that A_k is the maximum value of the total swept area for the monthly effort larger than zero.

9.2 Population dynamics

The model of Campbell *et al.* (2012) is summarised below. For simplicity, the notations used follow Campbell *et al.* (2012). We start with introducing the general form of the spatial-temporal model with information from the 1997–2015 fishing years. Then, we explain how to modify the model for the temporal data (i.e. fishing years 1978–1996).

9.2.1 Age-based population models

We denote N_{ijk} as the number of scallops at age j in spatial cell k at (monthly) time-step i, where $i = 1, \ldots, I$, $j = 1, \ldots, 48$, $k = 1, \ldots, K$. The number of scallops is modelled as follows:

$$N_{ijk} = \begin{cases} \Phi_{m_i} R_{ky_i} & \text{for } j = 1 \\ N_{i-1,j-1,k} e^{-Z_{i-1,j-1,k}} & \text{for } j = 2, \ldots, 48 \end{cases}, \qquad 9\text{-}1$$

where Φ_{m_i} is the weighting (proportion) of the annual recruitment for fishing-month m_i, R_{ky_i} is the annual recruitment in cell k in fishing year y_i, and Z_{ijk} is the total mortality rate for scallops of age j in cell k at time-step i. For Queensland's scallop fishery, a fishing year y is the period from 1 November of the calendar year $y - 1$ to 31 October of the calendar year y. Fishing-month $m = 1$ of the fishing year y represents November of the calendar year $y - 1$ and $m = 12$ of the fishing year y represents October of the calendar year y. Hence, when $m_{i+i'} = 1 + i'$, for $i' = 0, \ldots, 11$, $y = y_i = \cdots = y_{i+i'}$ as well as $R_{ky} = R_{ky_i} = \cdots = R_{ky_{i+i'}}$. For simplicity, we drop subscript i of y_i of R_{ky_i} such that $R_{ky} = R_{ky_i}$. Even so, keep in mind that y is corresponding to i.

The monthly weighting Φ_{m_i} of equation 9-1 is assumed to have the form of the von Mises distribution

$$\Phi_{m_i} = \frac{1}{2\pi I_0(\iota)} e^{\left(\iota \cos\left(\frac{2\pi(m_i - \vartheta)}{12}\right)\right)}, m_i = 1, \ldots, 12, \qquad 9\text{-}2$$

where ϑ is a location parameter, ι a concentration parameter, and $I_0(\cdot)$ the modified Bessel function of order 0. Here, ϑ and $1/\iota$ are analogous to the mean and variance of the normal distribution.

For annual recruitment R_{ky}, the model utilizes the Deriso-Schnute three parameter formulation and is written as

$$\frac{R_{ky}}{A_k / A_.} = \alpha P_{y-1} \left(1 - \beta \delta P_{y-1}\right)^{1/\delta}, \qquad 9\text{-}3$$

where P_y is the annual spawning stock size (i.e. egg production) in y, α the 'productivity' parameter, β the 'optimality' parameter, δ the 'recruitment limitation' parameter, and A_k and $A_.$ represent the area of cell k and the total area over the studied cells, respectively. For purposes of numerical stability while in the model fitting procedure, the logarithm of equation 9-3 is used, and temporal and spatial anomalies (i.e. deviations from the mean) are added to it. Hence, equation 9-3 can be rewritten as follows

$$\log\left(\frac{R_{ky}}{A_k/A_.}\right) = \log\left(\alpha P_{y-1} a_r \left(1 - \beta\delta P_{y-1} a_r\right)^{\frac{1}{\delta}}\right) + \log(b_r) + \xi_y + \psi_k, \quad 9\text{-}4$$

where a_r and b_r are given scalers, and ξ_y and ψ_k represent the temporal and spatial anomalies. For the anomalies, the summation of each anomaly is assumed to be zero (i.e. $\sum_y \xi_y = 0$, and $\sum_k \psi_k = 0$). Such an assumption takes advantage of ADMB to reduce occurrences of numerical issues (Fournier *et al.* 2012). To have the least impact on model fitting and parameter inferences, the penalties regarding temporal and spatial anomalies are added in the likelihood function (see Likelihood functions and data page 70 for details). For the two scalers, a_r and b_r were specified 10^{-10} and 10^4 in this study. We note that the assumption of zero for the two summed anomalies and values of the two scalers used by Campbell *et al.* (2012). In addition, the annual spawning stock P_y in fishing year y of equation 9-4 is modelled as

$$P_y = \sum_i \sum_j \sum_k I_{y_i=y}(i)\,\omega_{m_i} \frac{1-e^{-Z_{ijk}}}{2Z_{ijk}} N_{ijk} \eta_j \zeta_j, \quad 9\text{-}5$$

where $I_{y_i=y}(i)$ is an indicator function which is equal to 1 if $y_i = y$ and equal to 0 otherwise, w_{m_i} is the proportion of annual egg production occurring in fishing month m_i, and η_j and ζ_j are the proportion of scallop mature and the number of eggs produced by a scallop at age j, respectively.

The total mortality Z_{ijk} in equations 9-1 and 9-5 includes two mortality rates

$$Z_{ijk} = M + S_{ij} F_{ik}, \quad 9\text{-}6$$

where M is the instantaneous natural mortality rate, S_{ij} is selectivity for age j at time-step i, and F_{ik} is the instantaneous fishing mortality in cell k at time-step i. The fishing mortality F_{ik} in equation 9-6 is modelled as

$$F_{ik} = q_k f_y E_{ik}, \quad 9\text{-}7$$

where q_k is the catchability in cell k, f_y is the annual fishing power multiplier of fishing year y, and E_{ik} is the effort allocated to cell k at time-step i. Further, both q_k and E_{ik} in equation 9-7 are modelled as follows

$$q_k = \frac{pa}{A_k}, \quad 9\text{-}8$$

$$E_{ik} = \frac{(N_{i\cdot k}/A_k)^{\gamma} A_k \Gamma_{ik}}{\sum_{k'} (N_{i\cdot k'}/A_{k'})^{\gamma} A_{k'} \Gamma_{ik'}} \breve{E}_{i\cdot}, \quad 9\text{-}9$$

where p is the instantaneous catchability, a is a single unit of effort (i.e. boat-day), γ is the knowledge parameter, Γ_{ik} is the closure operator and $\breve{E}_{ik}$ is the observed effort (in boat-days) in cell k at time-step i. For the knowledge parameter γ, higher values attribute more effort in higher density areas. For Γ_{ik}, its value is 0 if cell k is closed to fishing at time-step i and 1 otherwise.

In equation 9-9, $N_{i\cdot k}$ represents the sum of N_{ijk} over age js and $\breve{E}_{i\cdot}$ represents the sum of $\breve{E}_{ik}$ over cell ks. The population dynamics introduced above (i.e. equations 9-1 to 9-9) provide a spatial-temporal framework for cases where the data (i.e. fishing years 1997–2015) have spatial and temporal components. However, in fishing years 1978–1996, the data only provide temporal information and contain the least information about fishing power and effort. Hence, modifications of some of the equations are needed.

For the temporal data, subscript k about cells in equations 9-1 to 9-9 can be removed. Given only the temporal information available, equation 9-9 is not required and equations 9-4 and 9-8 are modified as

$$\log(R_y) = \log\left(\alpha P_{y-1} a_r \left(1 - \beta\delta P_{y-1} a_r\right)^{\frac{1}{\delta}}\right) + \log(b_r) + \xi_y, \qquad \text{9-10}$$

$$q = p_{\text{early}} \kappa_{\text{early}} a/A., \qquad \text{9-11}$$

where p_{early} and κ_{early} are the instantaneous catchability and catchability index before fishing year 1997. With this modification, q_k and E_{ik} of equation 9-7 are replaced with q of equation 9-11 and the observed effort $\breve{E}_i$. However, in fishing years 1978–1988, observed effort and fishing power are not available. In this period, annual effort is modelled as a linear trend. This model is parameterised in terms of total effort at two reference years; 1980 and 1985, defined as E_{1980} and E_{1985}. Fishing power in the period is modelled as $f_{y_{\text{early}}}$

$$f_y = f_{\text{early}}^{(12-(y-1977))}, \; y = 1978, \ldots, 1988, \qquad \text{9-12}$$

where f_{early} is a hyperparameter less than 1.

Consequently, the population dynamic model can be divided into three time phases corresponding to properties of the available data. The first time phase is from the 1978 to 1988 fishing years, the second time phase from the 1989 to 1996 fishing years, and the third time phase from the 1997 to 2015 fishing years.

9.2.2 Deriving catch and catch rate

Based on the age-based population models in section 9.2, we derive catch C_{ik} for cell cell k at time-step i and catch rate u_i at time-step i

$$C_{ik} = b_r \sum_j \left(\frac{S_{ij} F_{ik}}{Z_{ijk}} w_j N_{ijk} \left(1 - e^{-Z_{ijk}}\right) \right), \qquad \text{9-13}$$

$$u_i = \frac{\sum_k C_{ik}}{f_y \breve{E}_i . \rho_{m_i}}, \qquad \text{9-14}$$

where w_j is the average weight (in kilograms) of scallop at age j, and ρ_{m_i} is the kilograms per basket for fishing-month m_i. Here, u_i represents catch per unit effort (CPUE) in baskets boat-day^{-1} at time-step i. Note that b_r is the scalar of equation 9-4 (i.e. $b_r = 10^4$). On the other hand, for the temporal data during fishing years 1978~1996, equations 9-13 and 9-14 were modified as follows

$$B_i = b_r \sum_j \left(S_{ij} w_j N_{ij} . e^{\frac{-Z_{ij}}{2}} \right), \qquad \text{9-15}$$

$$u_i = \frac{q f_y B_i}{\rho_{m_i}}, \qquad \text{9-16}$$

where B_i is the mid-month exploitable biomass, which is then multiplied by the catchability and fishing power components in equation 9-16 to predicted catch rates in baskets.

9.2.3 Likelihood functions and data

Since the data used for scallop stock assessment came from various sources, the -2 log likelihood L_{total} is a combination of the various dataset components

$$L_{\text{total}} = w_{u^{(1)}}L_{u^{(1)}} + w_{u^{(2)}}L_{u^{(2)}} + w_C L_C + w_{\text{Evms}}L_{\text{Evms}} + w_{R_s}L_{R_s} + w_\xi L_\xi + w_\psi L_\psi, \qquad \text{9-17}$$

where $L_{u^{(1)}}$, $L_{u^{(2)}}$, L_C, L_{Evms}, and L_{R_s} are the -2 log likelihood regarding the catch rate data from November 1977 to October 2015, the catch rate from January 1988 to October 2015, the annual catches from the 1978 to 2015 fishing years, the VMS effort, and the recruitment survey data, and L_ξ and L_ψ are the penalty terms regarding the temporal and spatial anomalies, respectively, and ws are their related weightings. Typically, values of $w_{\cdot}$s are specified.

For the monthly catch rate $u^{(1)} = [\breve{u}_1^{(1)}, \breve{u}_2^{(1)}, \ldots, \breve{u}_{456}^{(1)}]$, its logarithm is modelled using the normal distribution. The -2 log likelihood can be represented as follows

$$L_{u^{(1)}} = \sum_{i\in U^{(1)}}\left(\log\left(\sigma^2_{u^{(1)}}\right) + \frac{\left(\log\left(\breve{u}_i^{(1)}\right) - \log(u_i)\right)^2}{\sigma^2_{u^{(1)}}}\right), \qquad \text{9-18}$$

where $U^{(1)}$ is a set of indexes of valid months for $u^{(1)}$ and $\sigma^2_{u^{(1)}}$ is the variance. Here, the valid months refer to the months from November 1977 to October 2015 without including months of October from 2001 onwards as the fishery is closed as part of the annual southern closure (20 September–1 November). $\sigma^2_{u^{(1)}}$ is assumed to have an analytical form the same as the sample variance, that is, $\sigma^2_{u^{(1)}} = \sum_{i\in U^{(1)}}\left(\log\left(\breve{u}_i^{(1)}\right) - \log(u_i)\right)^2 / n_{U^{(1)}}$, where $n_{U^{(1)}}$ is the total number of valid months. Hence, equation 9-18 can be written as follows

$$L_{u^{(1)}} = n_{U^{(1)}}(\log\left(\sum_{i\in U^{(1)}}\left(\log\left(\breve{u}_i^{(1)}\right) - \log(u_i)\right)^2\right) - \log\left(n_{U^{(1)}}\right) + 1). \qquad \text{9-19}$$

Similar to $u^{(1)}$, the logarithm of the monthly catch rate $u^{(2)} = [\breve{u}_1^{(2)}, \breve{u}_2^{(2)}, \ldots, \breve{u}_{336}^{(2)}]$ is modelled using the normal distribution with the variance being replaced with the sample variance formula. The -2 log likelihood is:

$$L_{u^{(2)}} = n_{U^{(2)}}(\log\left(\sum_{i\in U^{(2)}}\left(\log\left(\breve{u}_i^{(2)}\right) - \log(u_i)\right)^2\right) - \log\left(n_{U^{(2)}}\right) + 1), \qquad \text{9-20}$$

where $U^{(2)}$ is a set of indices of valid months for $u^{(2)}$ and $n_{U^{(1)}}$ is the total number of valid months. The valid months here refer to the months from January 1988 to October 2015 without including months of October from 2001 onwards when the fishery is closed.

For the annual catch from 1978–2015, $C = [\breve{C}_{1978}, \breve{C}_{1979}, \ldots, \breve{C}_{2015}]$, its logarithm is modelled using the normal distribution with the variance having the sample variance form. For this dataset, the catch between 1978 and 1988 is from the historical annual catch of Dredge *et al.* (2016) and the catch between 1989 and 2015 is from CFISH data. For CFISH data, the annual catch is the sum of monthly spatial catch over the studied area for each 12-month block. The -2 log likelihood of the model is:

$$L_C = n_C(\log\left(\sum_y \left(\log(\breve{C}_y) - \log(C_y)\right)^2\right) - \log(n_C) + 1), \tag{9-21}$$

where n_C is the total number of fishing years, and $C_y = \sum_i \sum_k I_{y_i=y}(i) C_{ik}$, where is an indicator function which is equal to 1 if $y_i = y$ and equal to 0, otherwise.

For the VMS effort dataset from December 2000 to October 2015, the data are modelled using a multinomial formulation:

$$L_{\text{Evms}} = -2 \sum_{k \in K} \sum_{i \in I} n_{\text{Evms}} \breve{p}_{ik}^{(\text{Evms})} \log(p_{ik}^{(E)}), \tag{9-22}$$

where n_{Evms} is the total number of effective samples, $\breve{p}_{ik}^{(\text{Evms})}$ is the observed VMS effort in cell k at time-setp i as a proportion of total effort (i.e. the sum of effort over the studied space and time period), $p_{ik}^{(E)}$ is the model effort of equation 9-9 in cell k at time-setp i as a proportion, K is the index set of valid spatial cells and I is the index set of valid time-steps.

Similar to $u^{(1)}$, the survey data logarithm is modelled using the normal distribution with the variance having the sample variance form. We can write the likelihood function as

$$L_{R_s} = n_{R_s}(\log\left(\sum_y \left(\log(\breve{R}_{i_{\text{oct}},k}) - \log\left(\left(\sum_{j=2:6} N_{i_{\text{oct}},k,j}\right)/A_k\right)\right)^2\right) - \log(n_{R_s}) + 1), \tag{9-23}$$

where $\breve{R}_{i_{\text{oct}},k}$ is a (scaled) index of abundance of 0+ scallop (shell height less than 78mm) in cell k at time-step i_{oct} and n_{R_s} is the total number of valid samples. The time-step i_{oct} refers to October of a year.

Lastly, the two penalty terms L_ξ and L_ψ are assumed to be

$$L_\xi = \sum_y \log(\sigma_\xi^2) + \frac{\xi_y^2}{\sigma_\xi^2}, \tag{9-24}$$

$$L_\psi = \sum_k \log(\sigma_\psi^2) + \frac{\psi_y^2}{\sigma_\psi^2}, \tag{9-25}$$

where σ_ξ^2 and σ_ψ^2 are variances.

9.3 Stock assessment model inputs

Table 9-1 Biological parameters of the saucer scallop population used in the population dynamic model.

Parameters	Estimates	Data Sources
Shell Height (mm) h_j at age j to Weight w_j		
$w_j = ah_j^b$		
where a, b *and*	1.26E-09, 3.485	Courtney *et al.* (2007)
$h_j = L_\infty(1 - e^{-jc})$,		
where L_∞, c	106.026 SH mm; 0.225 month^{-1}	Williams and Dredge (1981)
Baskets to meat-weight conversion ρ_{m_i} (kg per basket)		O'Sullivan *et al.* (2005)
November	6.5	
December	7	
January	7	
February	7.5	
March	7	
April	6.5	
May	6	
June	5	
July	5	
August	5	
September	5.5	
October	6	
Natural Mortality (m)	0.09	Dredge (1985)
Shell Height (mm) h_j at age j to Fecundity ζ_j		
$\zeta_j = ah_j^b$		
where a, b	3220.708 (24558), 1.354 (1.665)	Dredge (1981)
Proportion mature, η_j at age, j		
$d = a + bj$, and $\eta_j = e^d/(1 + e^d)$		
where a, b	-0.794 (0.238), 0.178 (0.022)	Dredge (1981)
Monthly Spawning Pattern (ω_{m_i})		Dredge (1981)
November	0.0072	
December	0.0000	
January	0.0144	
February	0.0288	
March	0.0899	
April	0.1331	
May	0.1403	
June	0.1439	
July	0.1439	
August	0.1403	
September	0.0863	
October	0.0719	

Table 9-2 Phase settings and initial values for the model parameters and tuning parameters. Three phase settings are conducted. In phase settings, 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. If the number is equal to -1, the parameter is a tuning parameter (i.e. fixed in the optimization procedure). The range of the second column represents the lower and upper limits used for the ADMB optimization procedure. For E_{1985}, the first and second values are the annual effort in 1989 and the mean value of the annual effort of 1989 and 1990 from the CFISH data.

Parameter	Meaning (range)	Phase1	Phase2	Phase3	values
α	Stock-recruitment productivity parameter. (1,500)	1	1	1	[5, 15]
β	Stock-recruitment optimality parameter. (10^{-5}, 50)	2	2	2	0.16
ι	von Mises distribution measure of concentration – recruitment pattern. (0,∞)	4	3	4	[5, 10]
ϑ	von Mises distribution measure of location – recruitment pattern. ($-\infty$,∞)	2	1	2	[4, 8]
ϑ_E	von Mises distribution measure of location – early effort. (0,∞)	1	2	1	equal to ϑ
$\log(p)$	Logarithm of instantaneous catchability. (-6,6)	3	3	2	[log(0.3), log(0.6)]
ξ_i	Temporal recruitment anomaly for year i. (-5,5)	2	2	2	0
$\log(\sigma_\xi)$	Logarithm of standard deviation of temporal recruitment process errors. (-6,5)	4	2	4	-1
ψ_k	Spatial recruitment anomaly in cell k. (-5,5)	3	3	3	0
$\log(\sigma_\psi)$	Logarithm of standard deviation of spatial recruitment process errors. (-6,5)	4	3	4	-1
κ_{early}	Catchability index prior to November 1996. (0,∞)	1	2	1	1
E_{1980}	Annual effort in 1980. (1, 50000)	3	2	4	5000
$\log(p_{\text{early}})$	Logarithm of instantaneous catchability prior to November 1989. (-6,6)	3	1	3	log(0.5)
δ	Stock-recruitment limitation parameter	-1	-1	-1	-0.99999
F_{pre}	Fishing mortality prior to 1978	-1	-1	-1	10^{-6}
M	Natural mortality	-1	-1	-1	0.09
ι_E	von Mises distribution measure of concentration – recruitment pattern pre-1989	-1	-1	-1	0.81
f_{early}	Fishing efficiency prior to 1989	-1	-1	-1	0.99
$\log(\gamma)$	Knowledge parameter	-1	-1	-1	[log(1), log(2)]
E_{1985}	Annual effort in 1985	-1	-1	-1	[4422.298, 9583.265]

Table 9-3 The algorithm to construct 64 scenarios according to $log(\gamma)$, E_{1985}, α, ι, ϑ, ϑ_E and $log(p)$. Each parameter involves two values. Note that ϑ and ϑ_E use the same initial values in each scenario.

```
Do $\log(\gamma) = (\log(1),\log(2))$
  Do $E_{1985} = (4422.298, 9583.265)$
    Do $\alpha = (5, 15)$
      Do $\iota = (5,10)$
        Do $\vartheta = \vartheta_E = (4, 8)$
          Do $\log(p) = (\log(0.3),\log(0.6))$
          End Do
        End Do
      End Do
    End Do
  End Do
End Do
```

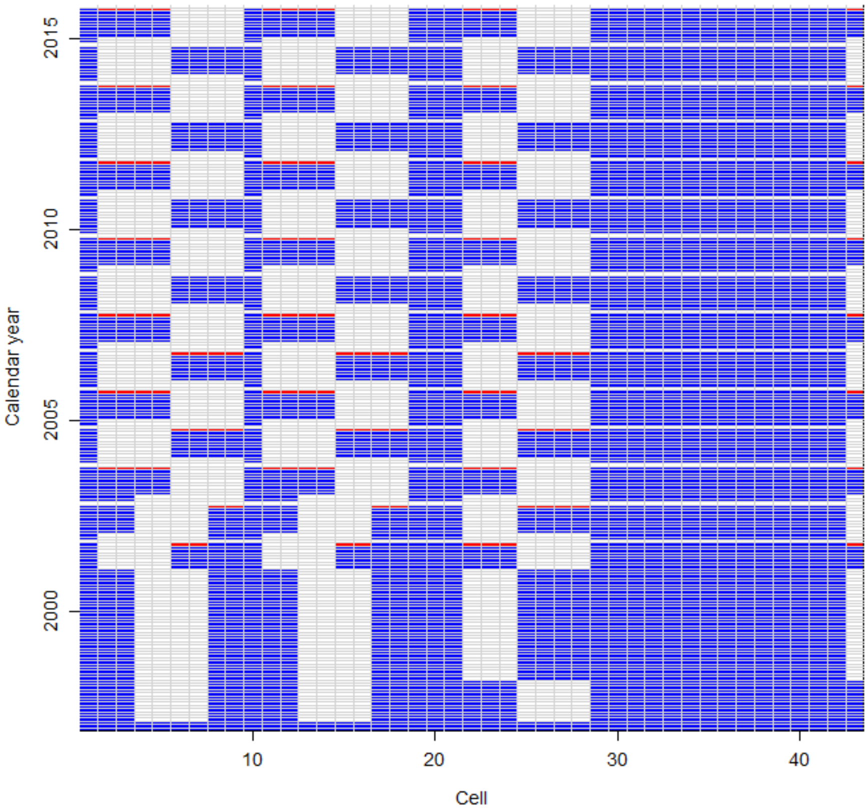

Figure 9-3 Closure schedules of 43 cells from November of 1996 to October of 2015. Blue, white and red represent open, closed and closed for roughly half of the month, respectively.

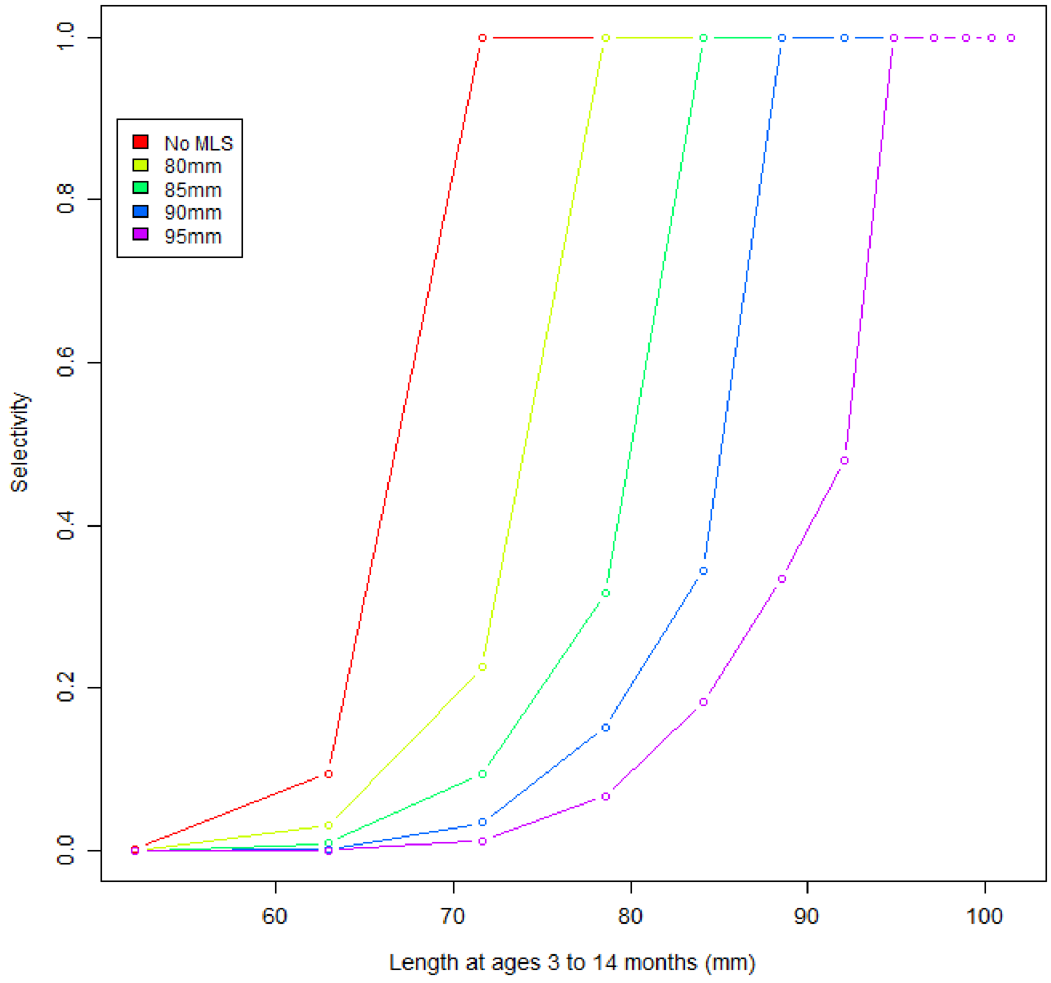

Figure 9-4 Selectivity curves used from November 1977 to October 2015. These curves were used as follows: 1) November 1977 to October 1980: red curve; 2) November 1980 to October 1984: yellow curve; 3) November 1984 to October 1987: green curve; 4) November 1987 to December 1999: blue curve for November to April and purple curve for May to October; 5) January 2000 to October 2004: blue curve for January to April and purple curve for May to December; 6) November 2004 to October 2009: blue curve for November to April and purple curve for May to October; 7) November 2009 to October 2015: blue curve.

9.4 Detailed assessment outputs and results

9.4.1 Model M1

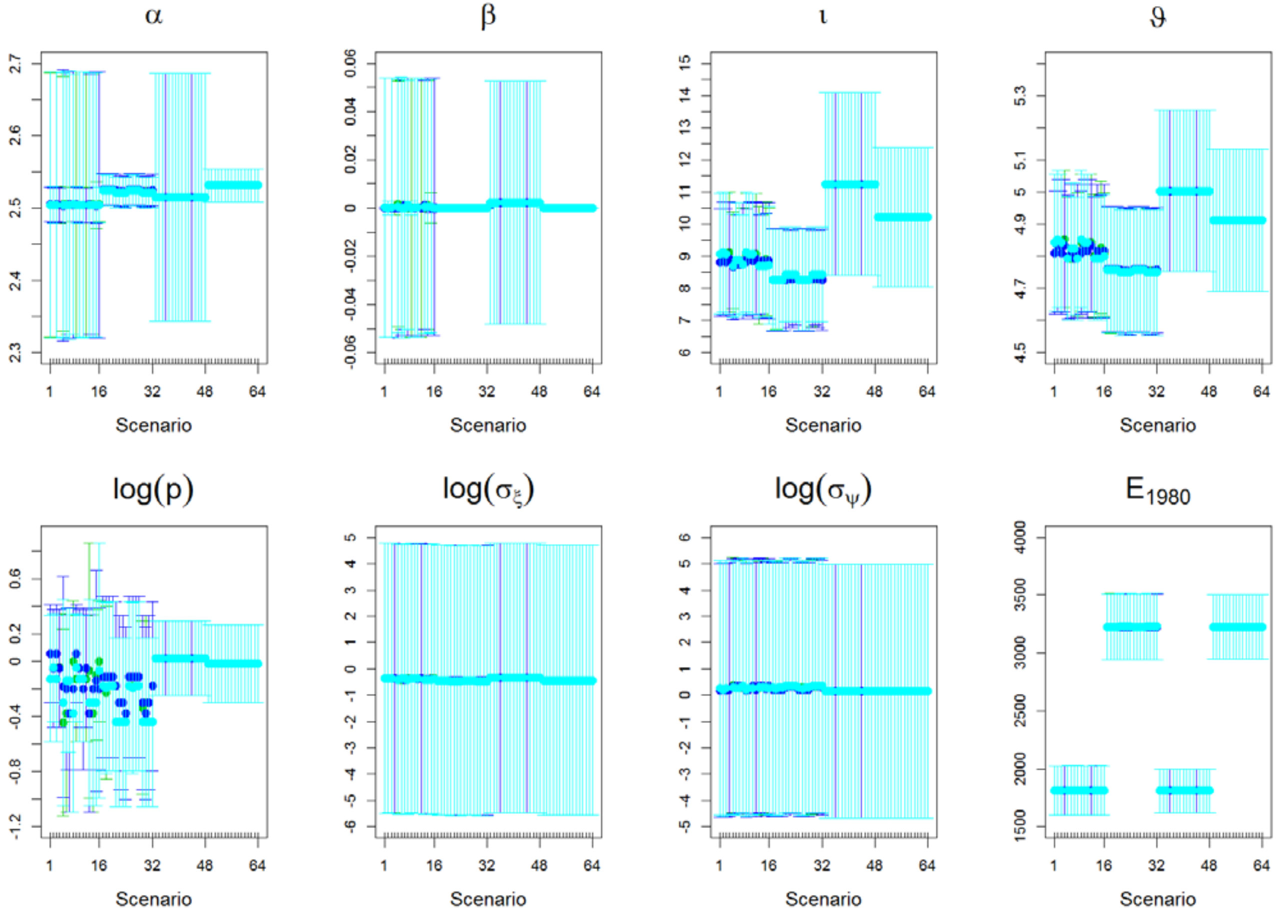

Figure 9-5 Means (solid circles) and ± two standard errors (bars) for the parameters and outputs of M1. Green, blue and light blue represent Phase 1, 2 and 3, respectively.

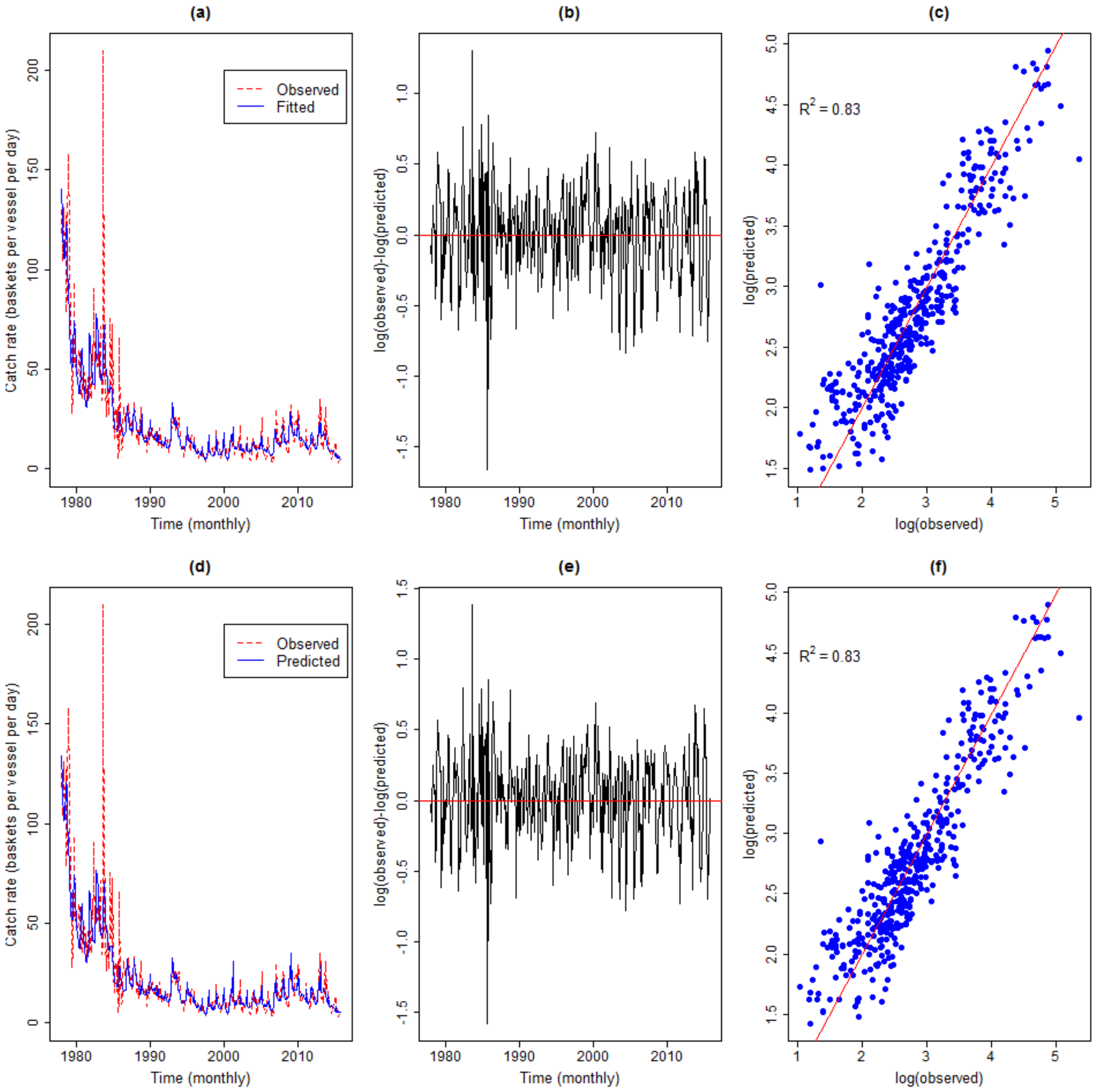

Figure 9-6 Outputs used to evaluate the performance of M1 for predicting $u^{(1)}$ in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

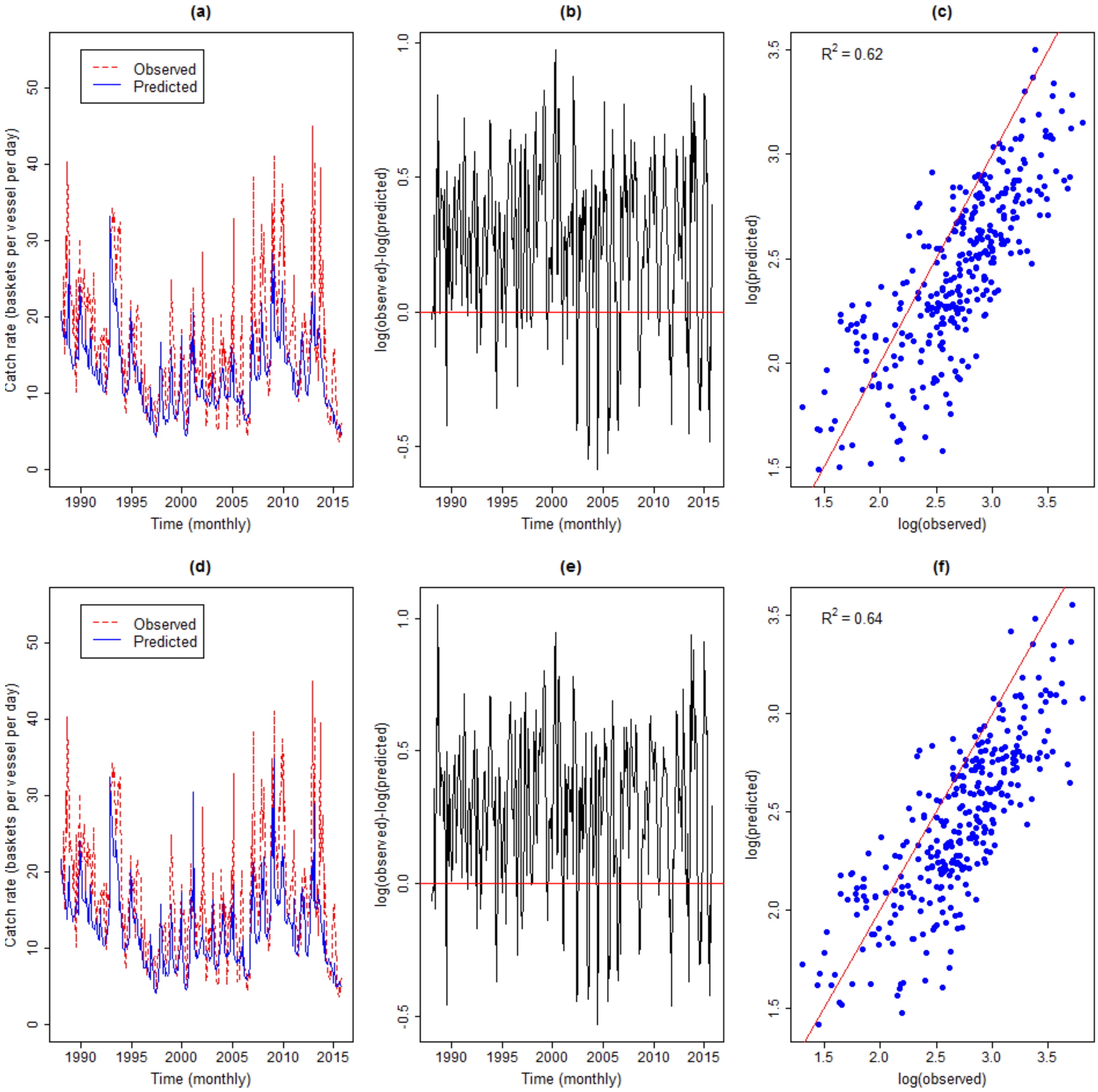

Figure 9-7 Outputs used to evaluate the performance of M1 for predicting $u^{(2)}$ in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

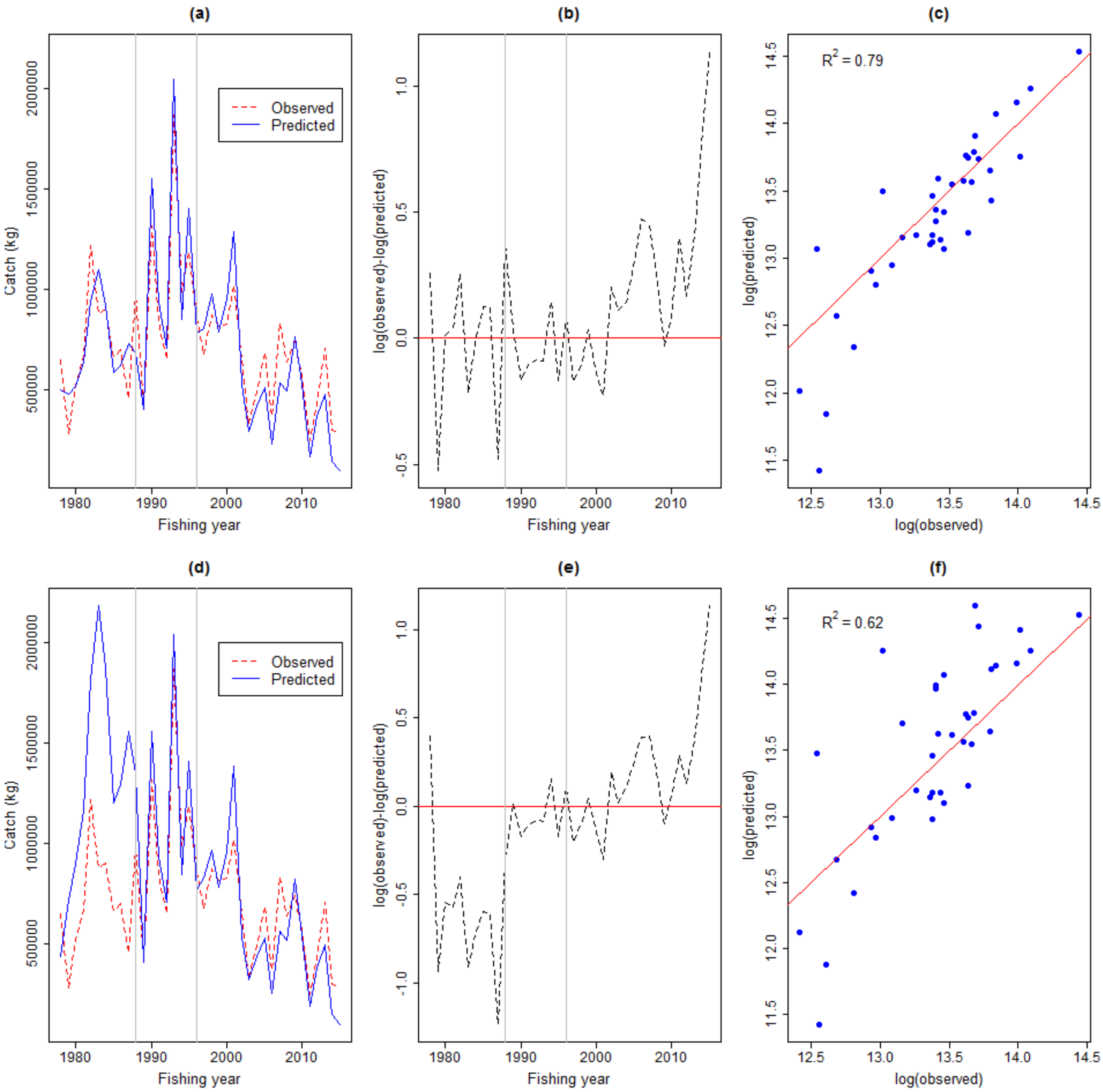

Figure 9-8 Outputs used to evaluate the performance of M1 for predicting the annual catches of fishing years from 1978 to 2015 in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

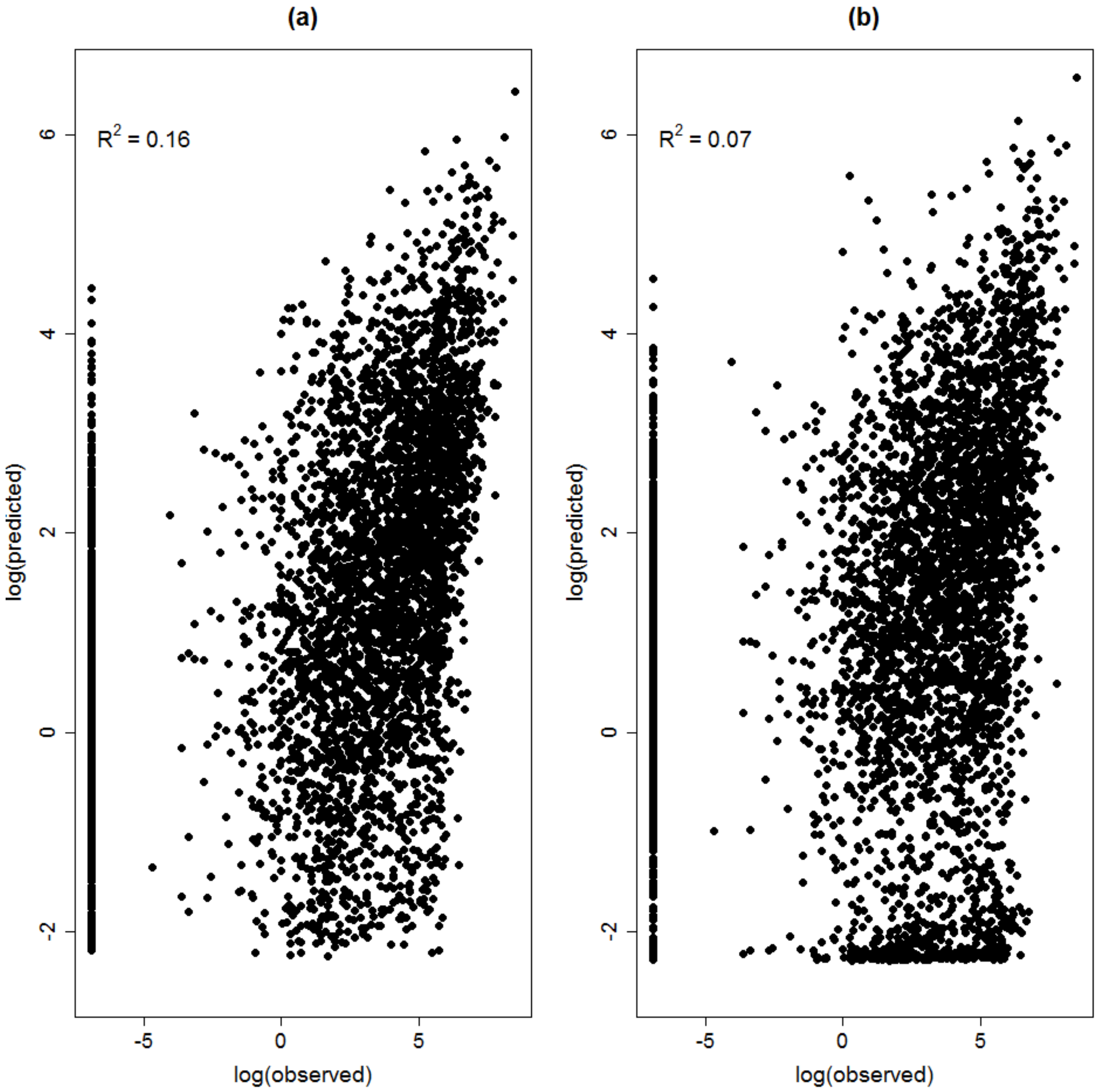

Figure 9-9 Evaluating the performance of M1 for predicting E_{VMS} in scenario 1 (a) and 64 (b) of Phase 2.

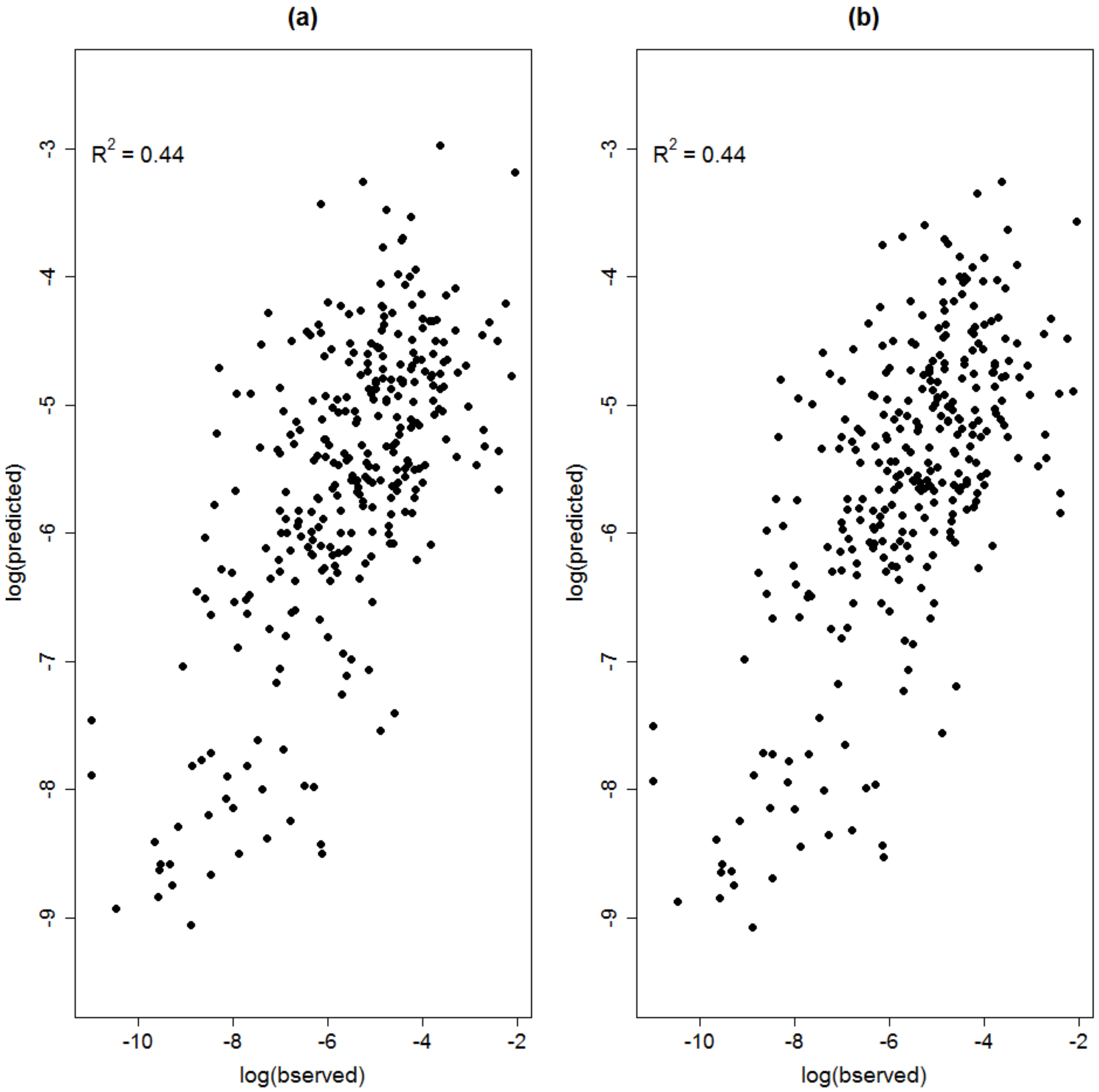

Figure 9-10 Evaluating the performance of M1 for predicting R_s in scenario 1 (a) and 64 (b) of Phase 2.

9.4.2 Model M2

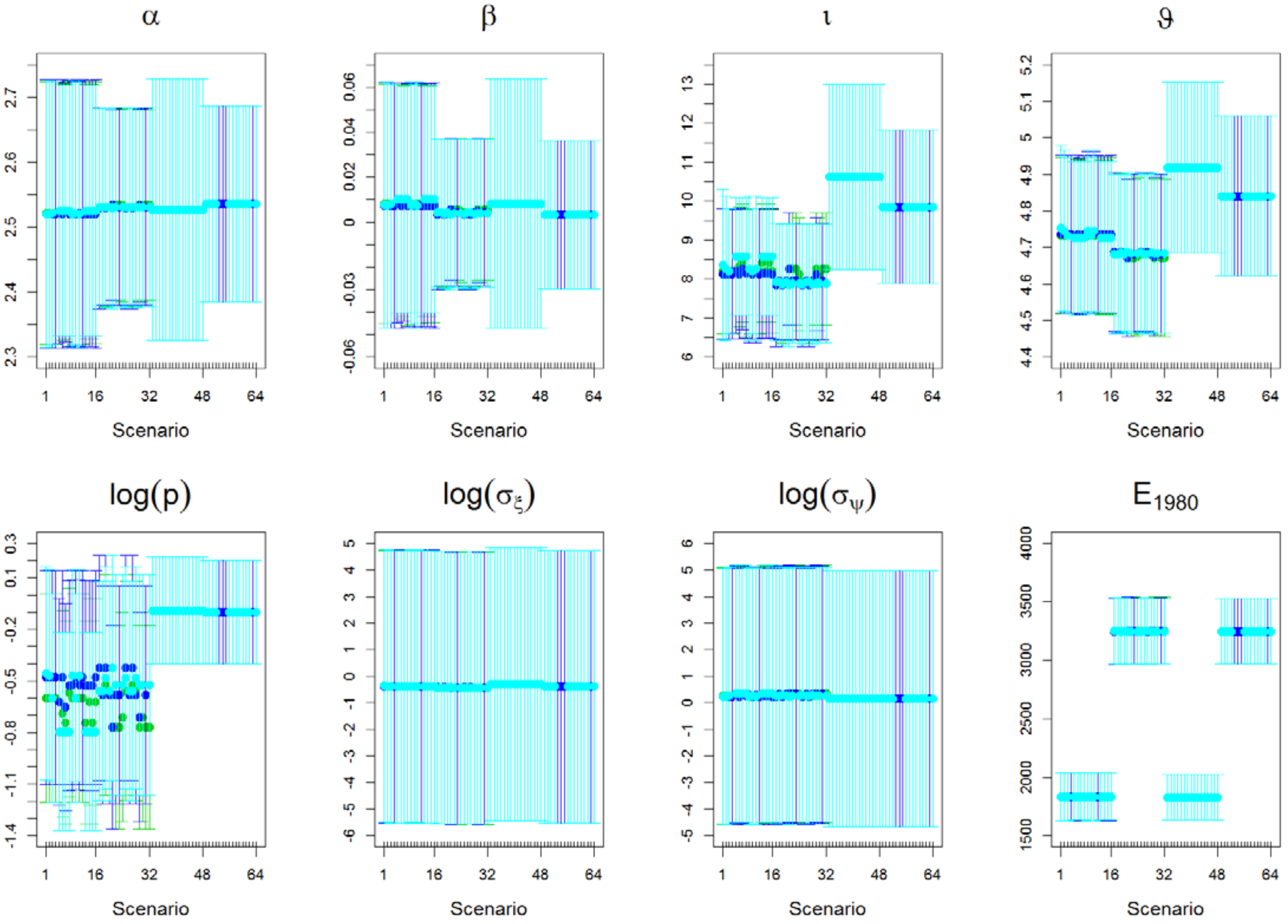

Figure 9-11 Means (solid circles) and ± two standard errors (bars) for the parameters and outputs of M2. Green, blue and light blue represent Phase 1, 2 and 3, respectively.

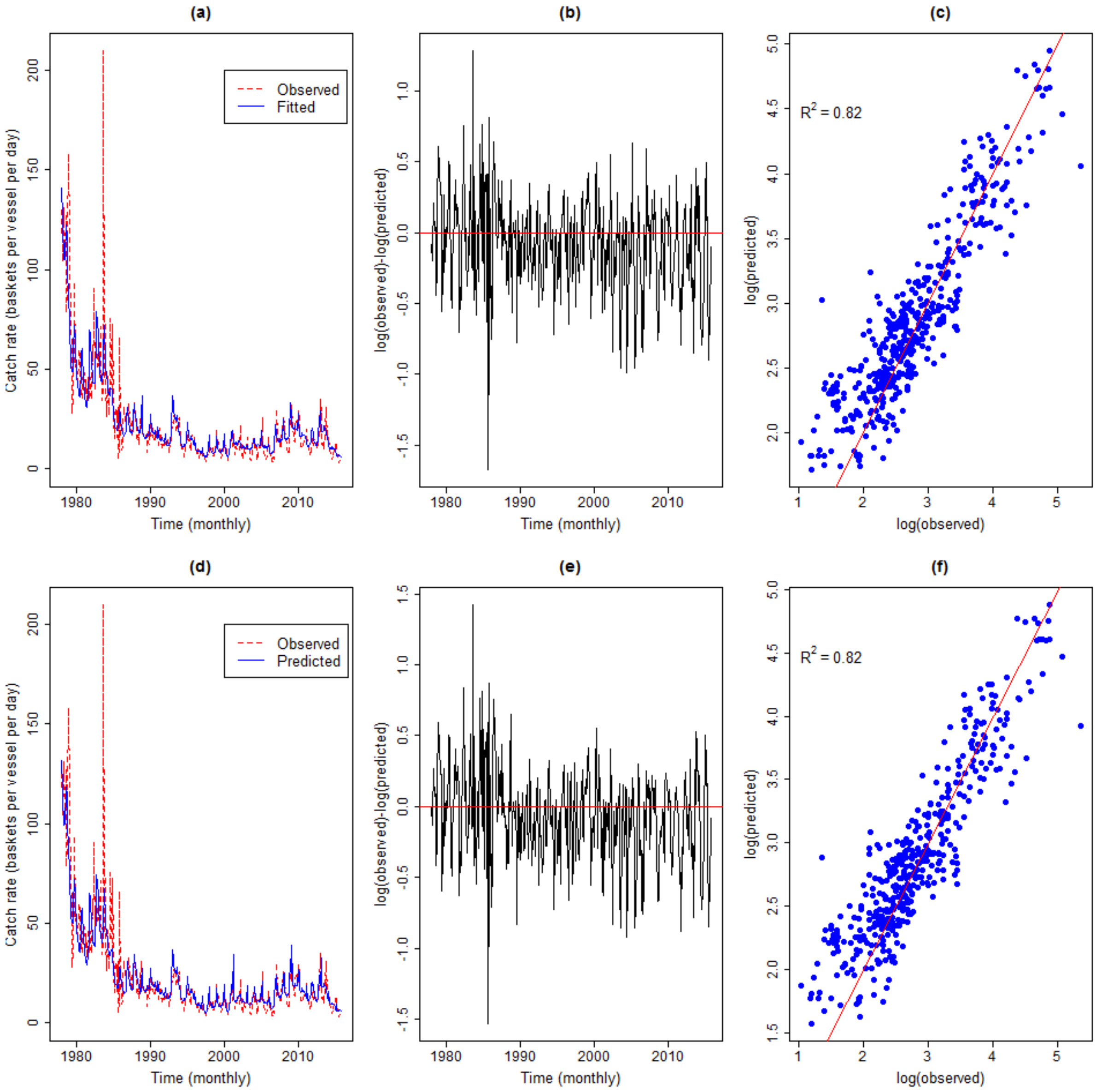

Figure 9-12 Outputs used to evaluate the performance of M2 for predicting $u^{(1)}$ in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

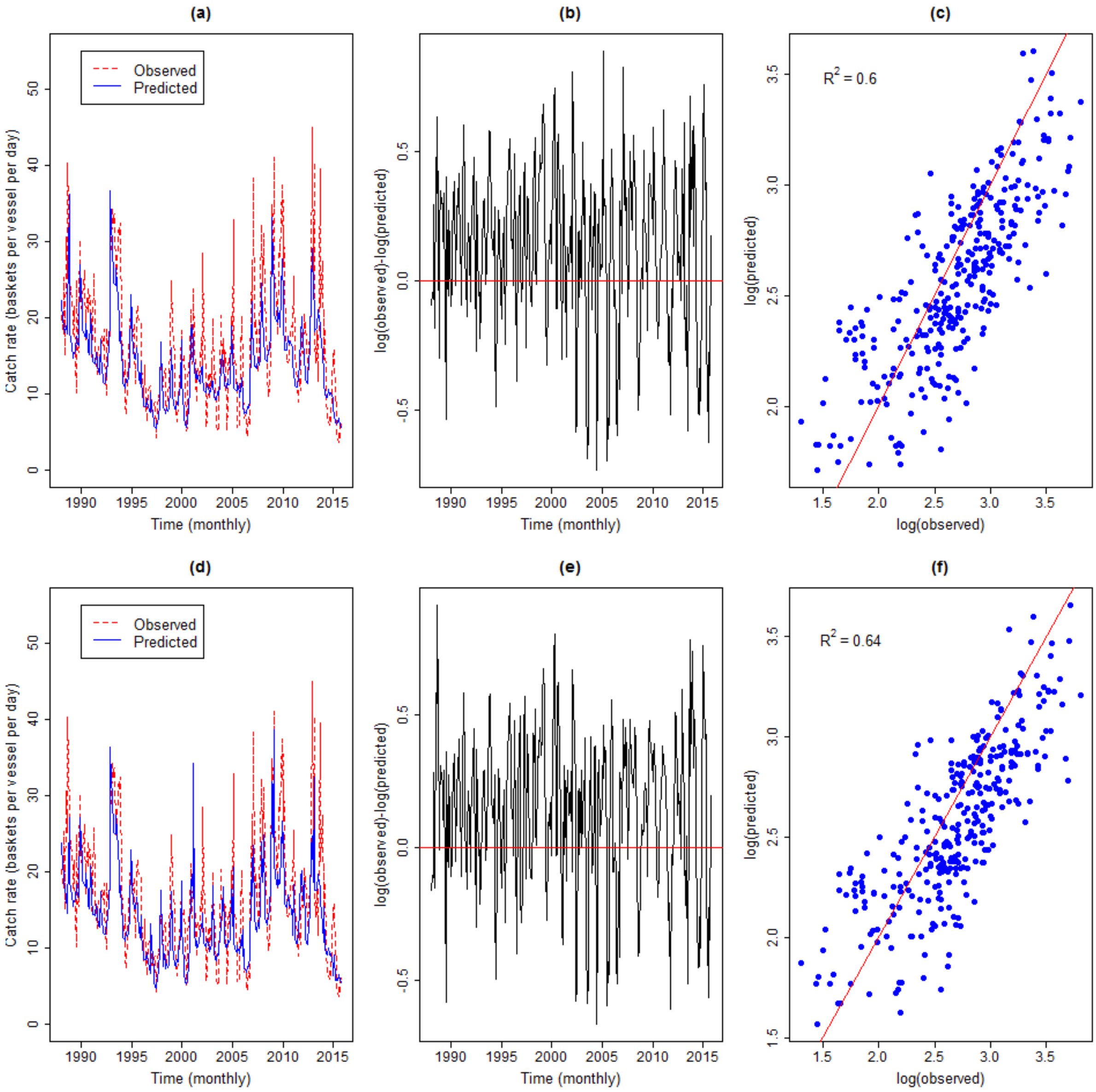

Figure 9-13 Outputs used to evaluate the performance of M2 for predicting $u^{(2)}$ in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

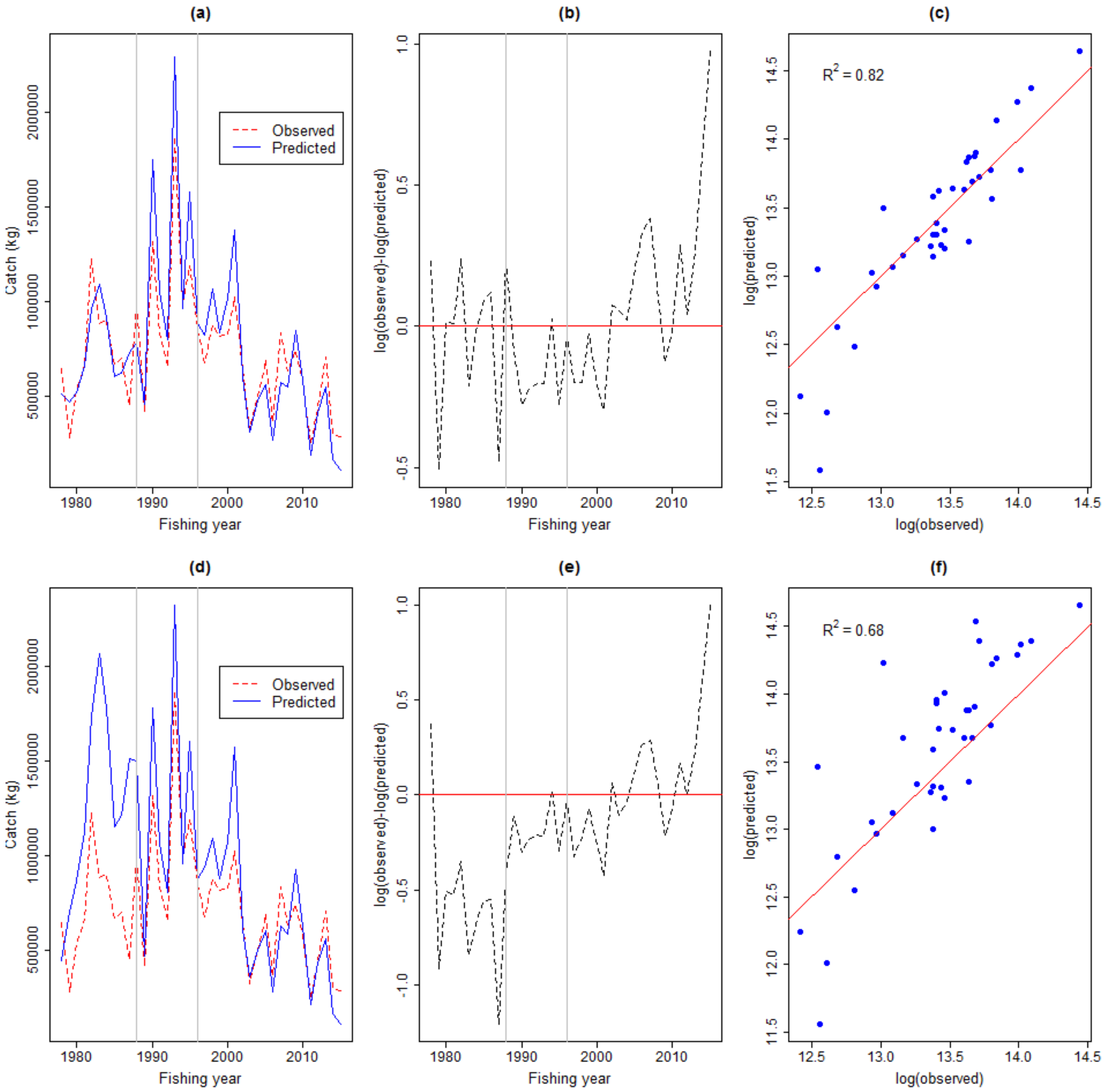

Figure 9-14 Outputs used to evaluate the performance of M2 for predicting the annual catches of fishing years from 1978 to 2015 in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

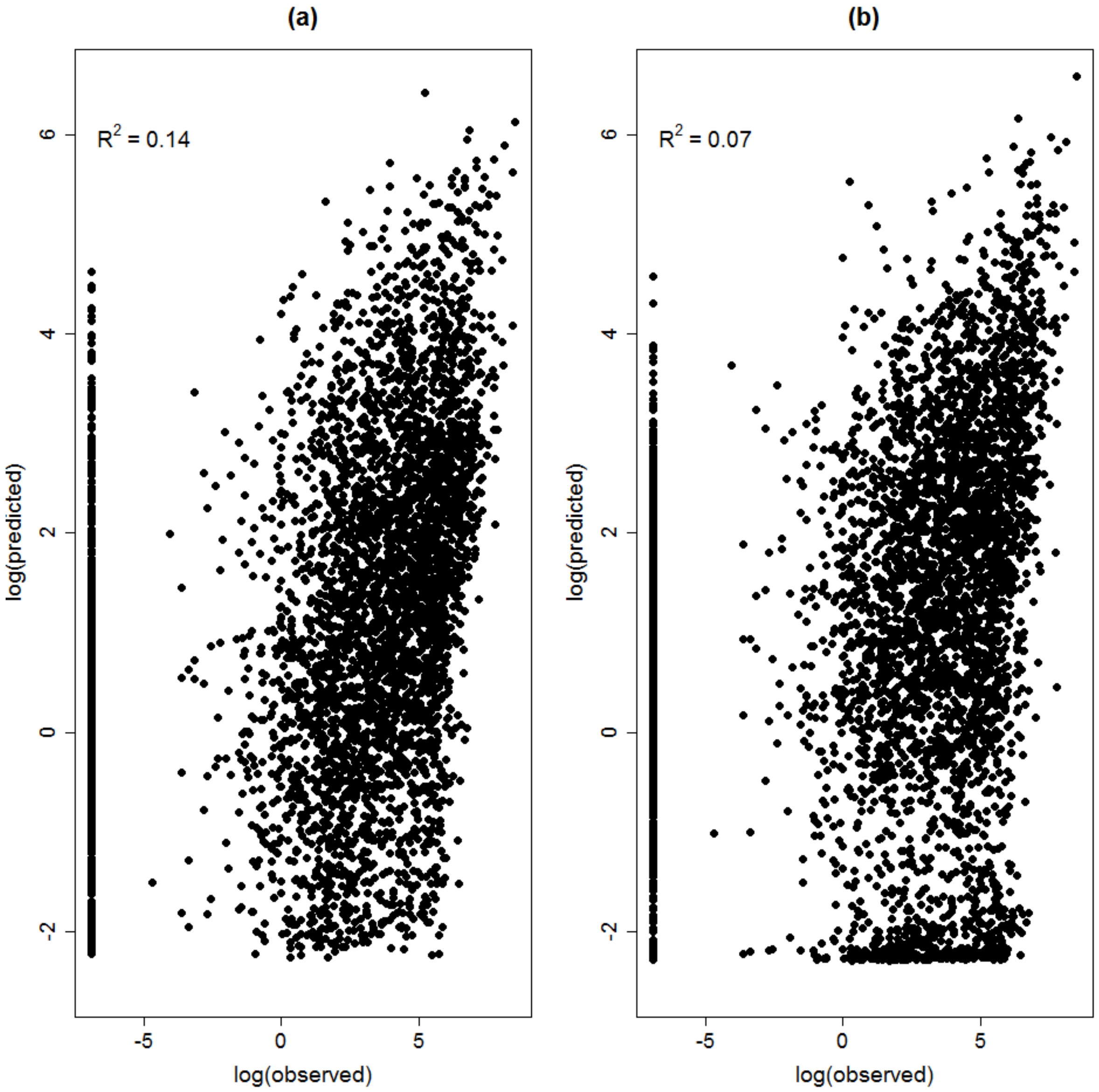

Figure 9-15 Evaluating the performance of M2 for predicting E_{VMS} in scenario 1 (a) and 64 (b) of Phase 2.

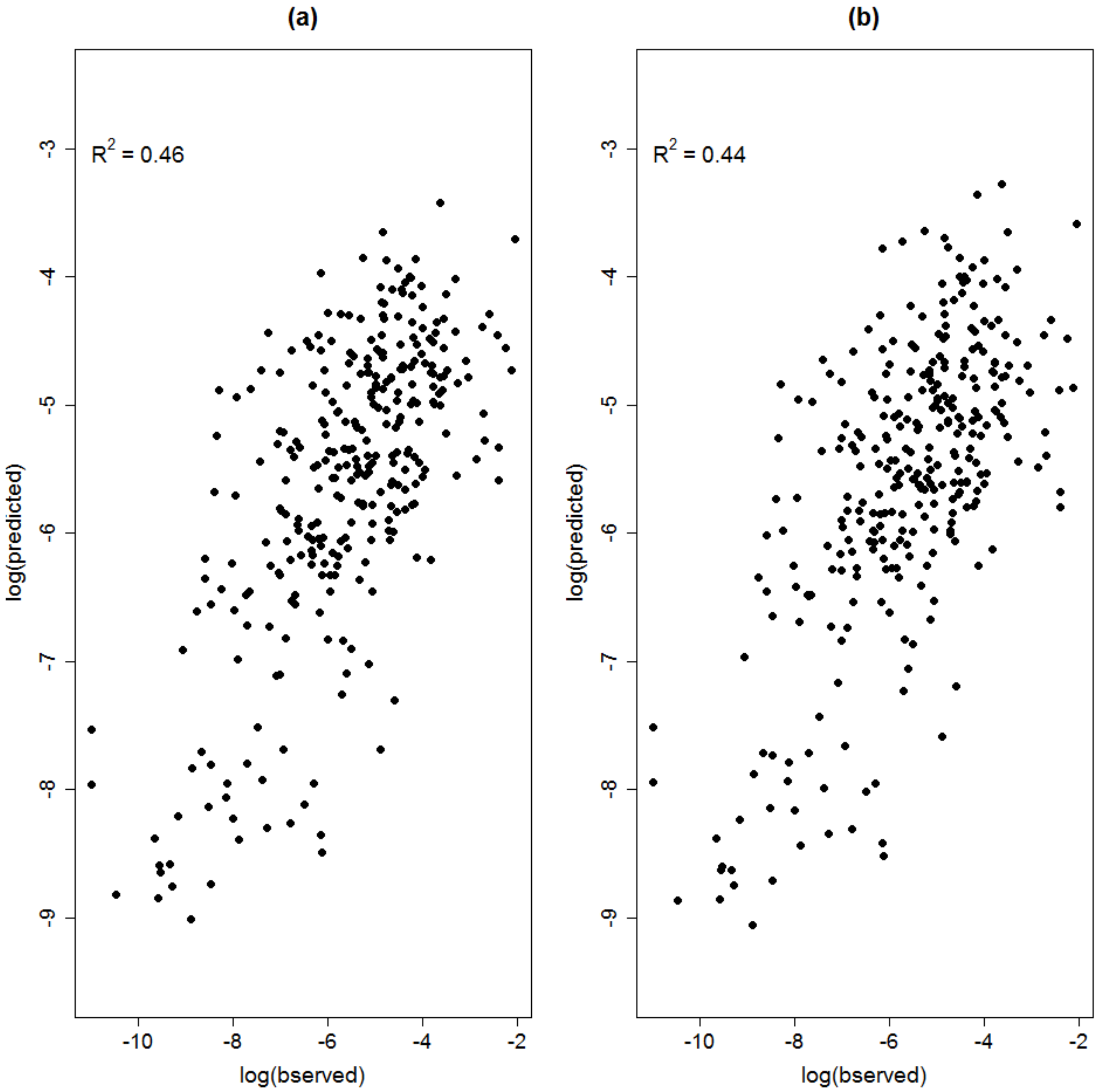

Figure 9-16 Evaluating the performance of M2 for predicting R_s in scenario 1 (a) and 64 (b) of Phase 2.

9.4.3 **Model M3**

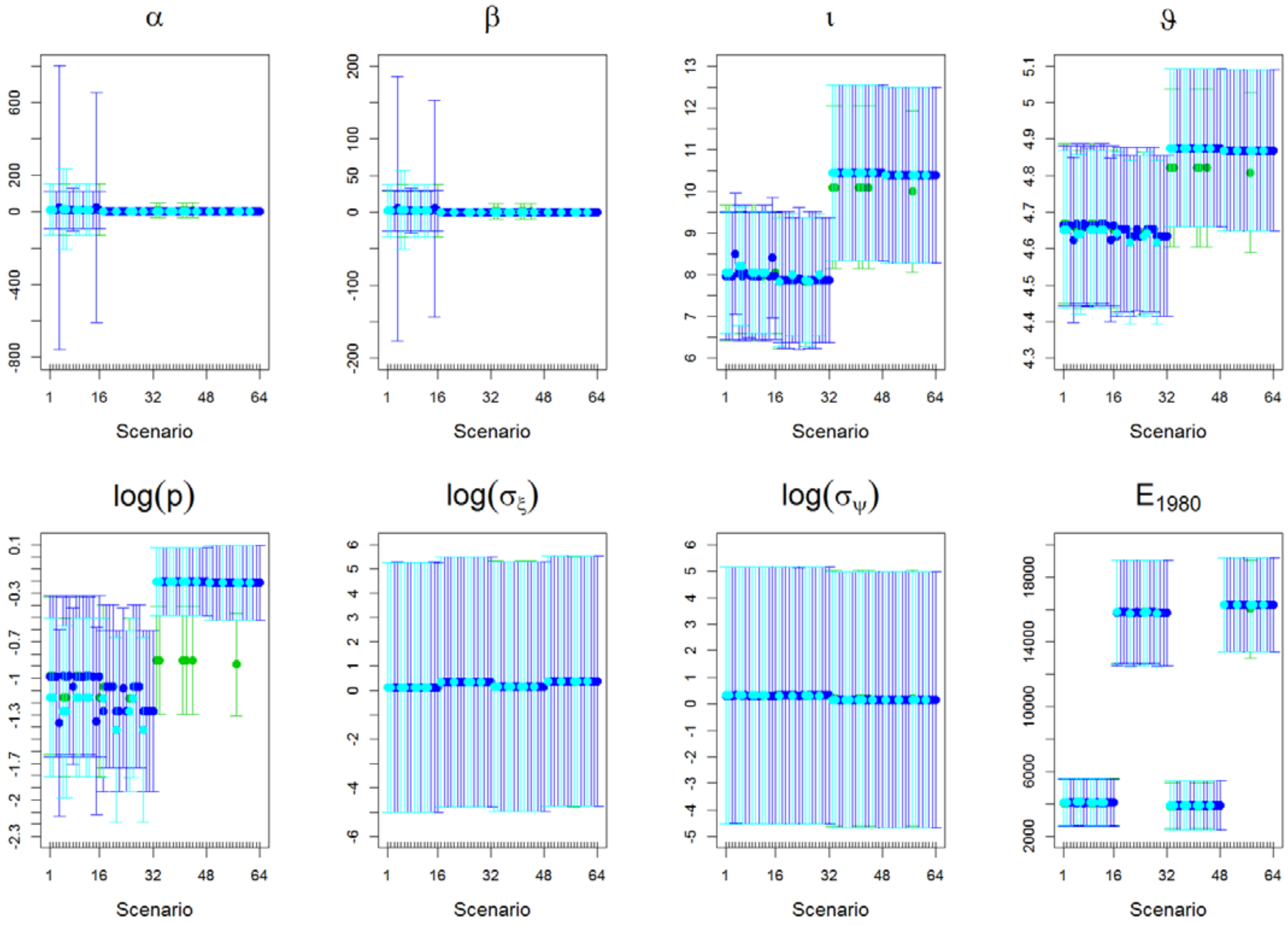

Figure 9-17 Means (solid circles) and ± two standard errors (bars) for the parameters and outputs of M3. Green, blue and light blue represent Phase 1, 2 and 3, respectively.

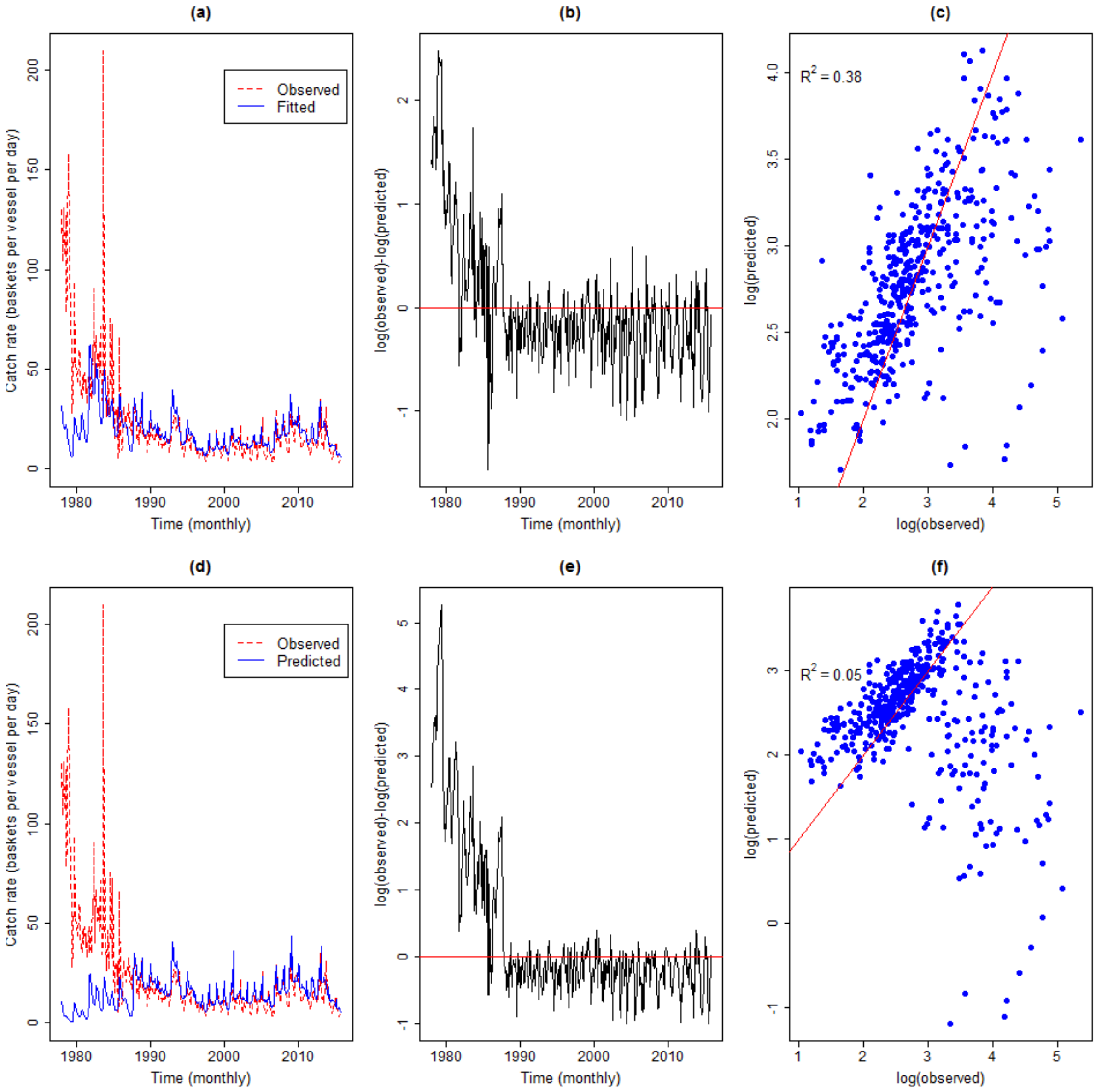

Figure 9-18 Outputs used to evaluate the performance of M3 for predicting $u^{(1)}$ in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

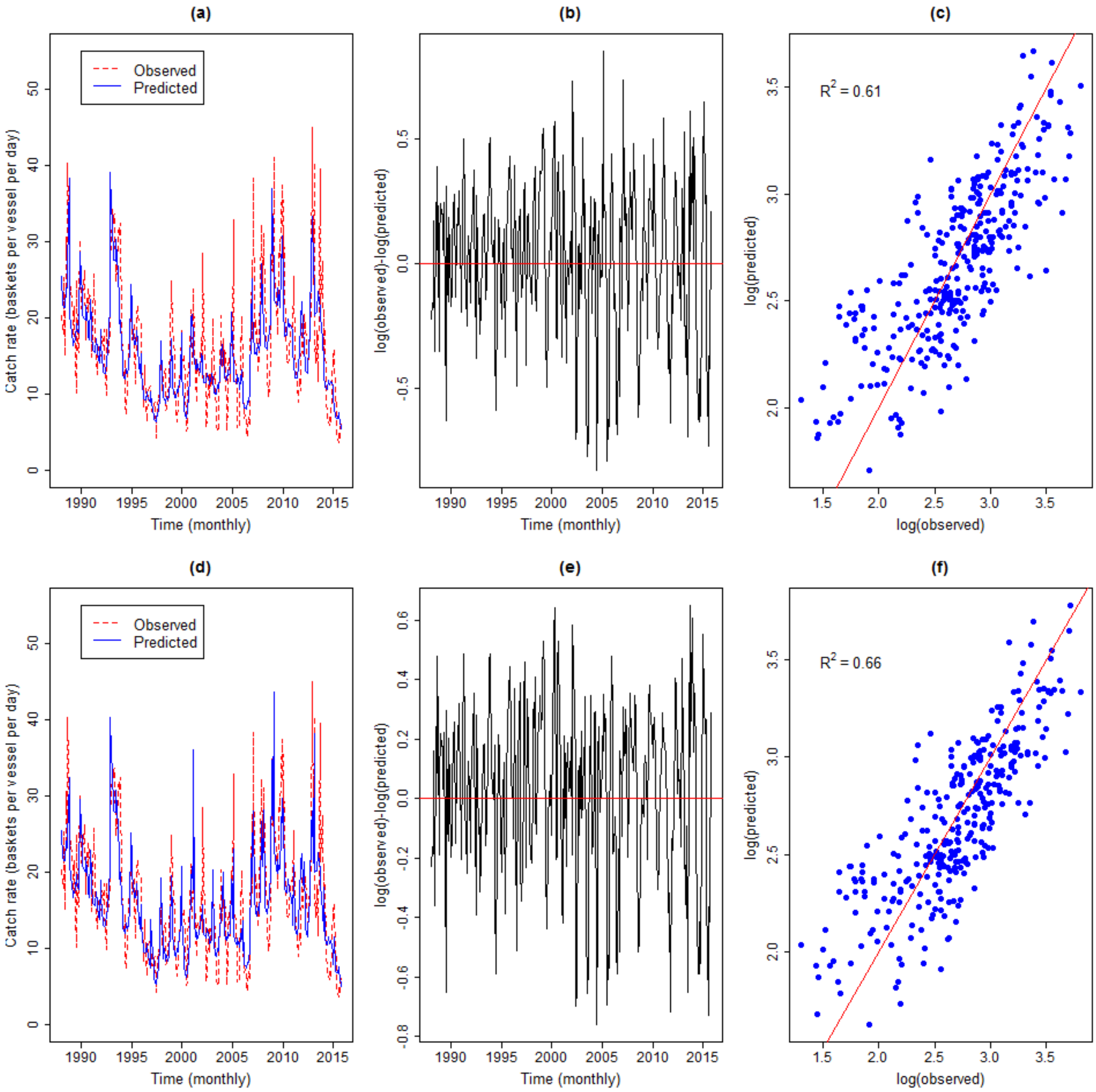

Figure 9-19 Outputs used to evaluate the performance of M3 for predicting $u^{(2)}$ in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

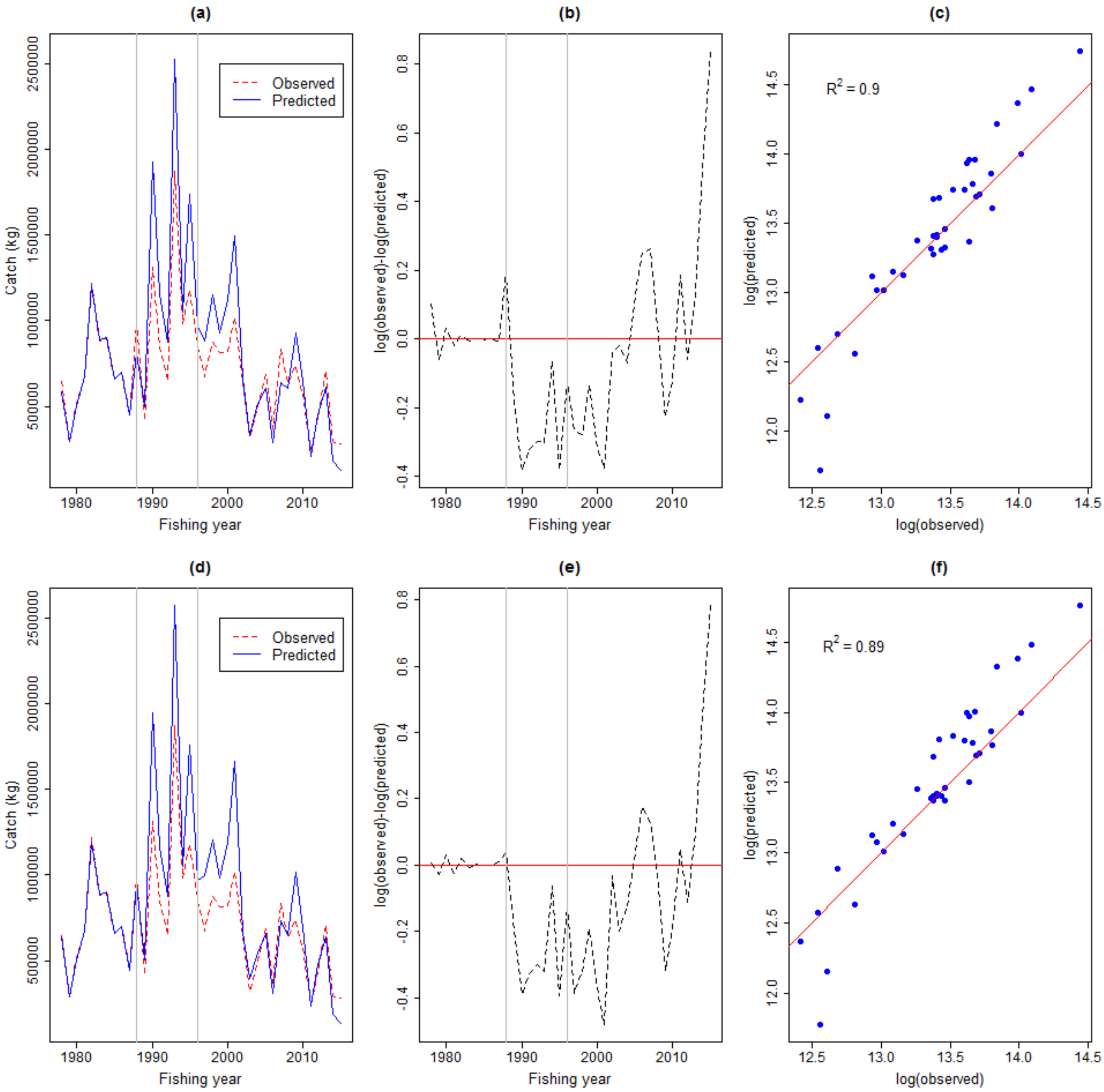

Figure 9-20 Outputs used to evaluate the performance of M3 for predicting the annual catches of fishing years from 1978 to 2015 in scenario 1 ((a)-(c)) and 64 ((d)-(f)) of Phase 2.

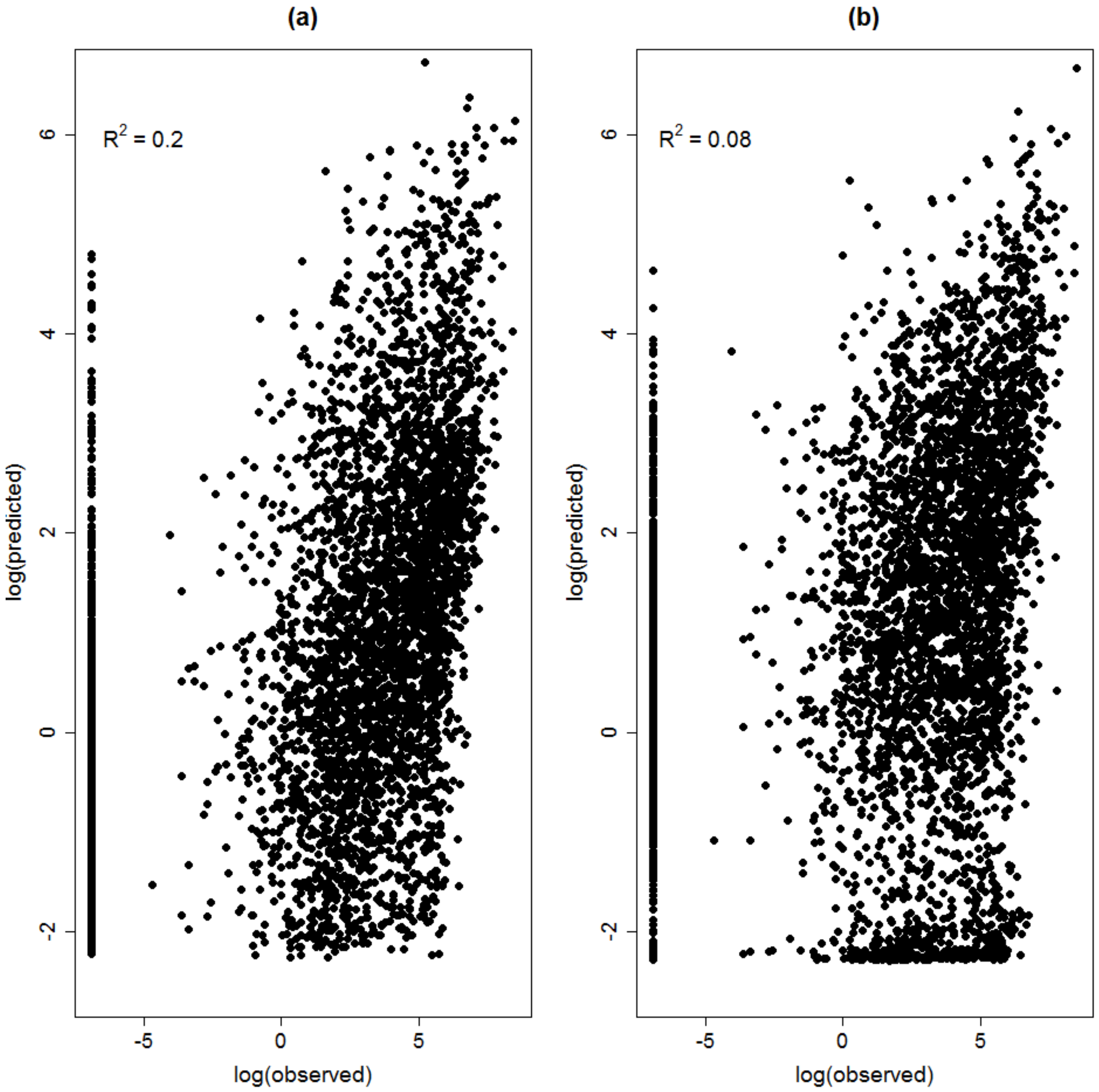

Figure 9-21 Evaluating the performance of M3 for predicting E_{VMS} in scenario 1 (a) and 64 (b) of Phase 2.

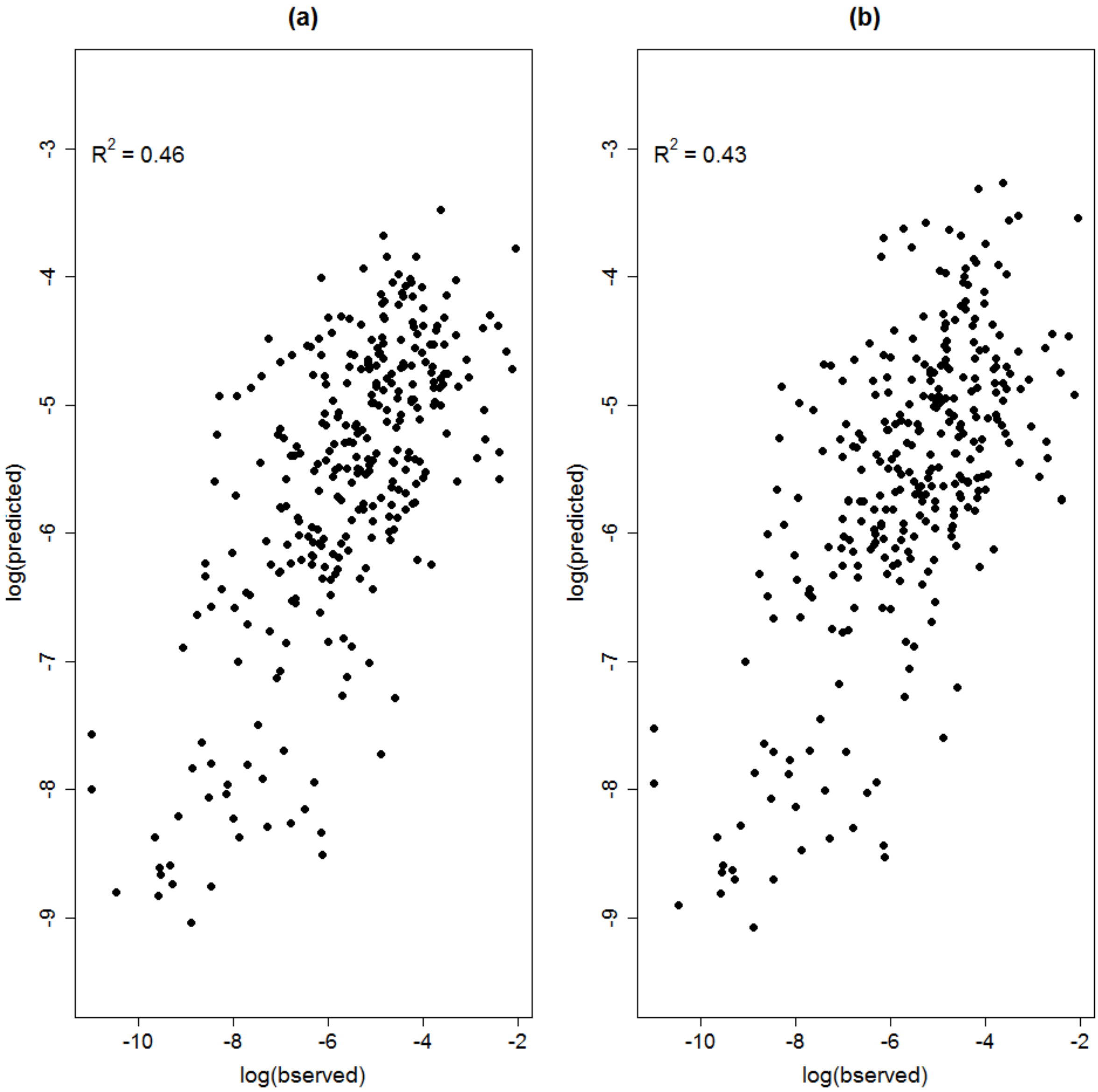

Figure 9-22 Evaluating the performance of M3 for predicting R_s in scenario 1 (a) and 64 (b) of Phase 2.