A bio-economic model for South Australia's prawn trawl fisheries

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PREMIUM FOOD AND WINE FROM OUR CLEAN ENVIRONMENT

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Non-technical summary

2011/750. A bio-economic model for South Australia's prawn trawl fisheries

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OUTPUTS PRODUCED

1. The first bio-economic model for the Western King Prawn (WKP, *Penaeus (Melicertus) latisulcatus*) developed for the Gulf St Vincent Prawn Fishery (GSVPF) and Spencer Gulf Prawn Fishery (SGPF) in South Australia.
2. The most comprehensive attempt thus far to integrate standardised catch histories, WKP population dynamics and vessel-based economic data for these fisheries.
3. Estimated reference points that relate to maximum sustainable yield (MSY) and maximum economic yield (MEY) for each fishery at status quo and increased fishing power and costs.
4. A tool for providing managers and stakeholders with improved information about the current status of the WKP stocks relative to model-estimated reference points, and how the stocks might respond to specific management actions.

OUTCOMES ACHIEVED TO DATE

1. Acknowledgment from PIRSA Fisheries and Aquaculture that the bio-economic model will play an important role in the development of future harvest strategies for the GSVPF and SGPF.
2. For the SGPF, PIRSA Fisheries and Aquaculture, SARDI Aquatic Sciences and industry have recently agreed on a stock assessment development program over the next few years, in which the bio-economic model will comprise one of the tools available to assist with the program. This strategy will improve the likelihood of adoption of the model in the SGPF.

ABSTRACT

In recent years, Australian wild catch prawn fisheries have experienced reduced profits due to increased fishing costs, static prawn prices and market competition from importation of cheap aquaculture prawns. The Gulf St Vincent Prawn Fishery (GSVPF) and Spencer Gulf Prawn Fishery (SGPF) of South Australia are two such fisheries in which general economic performance (e.g. profits) in recent years has become a concern. Both fisheries target a single species, the Western King Prawn (WKP, *Penaeus (Melicertus) latisulcatus*), with combined annual harvests of ~2200 t and a landed value of ~\$33M. To improve the profitability for the GSVPF and SGPF, the vessels in which are characteristically operated for only a fraction of the year (less than 10-20% of the year), this project focused on the development of a bio-economic model for these WKP fisheries. The main outputs of the model are WKP population and economic status based on reference points for maximum sustainable yield (MSY) and maximum economic yield (MEY), and evaluation of 10-year projections of simulated management procedures for each fishery. Simulations indicated that the best performing procedures (mainly with respect to economic performance measures) were those that involved a reduction in the number of vessels, and for SGPF, a closure in November, or a closure in June offset with an increase in the pre-Christmas harvest. Subject to further development to improve the reliability of outputs, the WKP bio-economic model should be a useful tool for providing managers and stakeholders with improved information about the current status of the WKP stocks relative to their biological reference points, and how the stocks might respond to specific management actions.

The reported declines in profitability in wild catch prawn fisheries have prompted fisheries management to pursue more profitable objectives such as MEY than MSY, and these are achieved with the development and application of a bio-economic model. The bio-economic model developed in this project was based on the model recently developed for the Eastern King Prawn fishery of New South Wales and Queensland. The model represents the most comprehensive attempt thus far to integrate standardised catch histories, WKP population dynamics and vessel-based economic data for the South Australian fisheries. Most bio-economic models are built as extensions of pre-existing fully-formed stock assessment model estimators. This was the case for Tasmanian (Punt and Kennedy, 1997), Western Australian (Hall, 2000) and South Australian rock lobster fisheries (McGarvey *et al.*, 2014), and the Northern Prawn Fishery (Dichmont *et al.*, 2008; Punt *et al.*, 2010). In the current project, we built a potentially powerful management tool for South Australia's WKP fisheries. In particular, we constructed a fully-formed length-based stock assessment model that incorporates all available bio-economic data and includes a projection component able to test a range of management strategies.

Provisional estimates of annual reference points for MSY and MEY were highly dependent on the economic parameters and status quo effort levels and monthly effort pattern. MSY was estimated at ~370 t for the GSVPF and ~2740 t for the SGPF, and MEY estimates were at ~320 t and ~2170 t, respectively. Effort levels required to achieve MEY (E_{MEY}) were lower with indicative increases in fishing power (and associated vessel and fuel costs) expected with smaller fleet sizes. Mean monthly catch rate reference points corresponding to MEY were ~570 kg block^{-1} vessel-night^{-1} for the GSVPF; retrospective comparison with logbook data confirmed a reduced stock in the 2012 fishing year prior to the closure of the fishery (primarily due to economic concerns) in 2013. For the SGPF, MEY reference points ranged between 540 and 870 kg block^{-1} vessel-night^{-1}, and indicated that the exploitable biomass in this fishery has been higher than the biomass at MSY since 1991.

Various candidate management procedures were developed in consultation with industry and government (10 for the GSVPF; 14 for the SGPF), and these included reductions in the number of vessels to reduce the apparent over-capitalisation, increases in effort, changes in the pre-Christmas catch cap (which coincides with peak spawning of WKP), spatial and/or temporal closures, and introduction of a harvest (output) quota. A holistic approach was used to evaluate each procedure, where we not only took into account the predicted catch rates and economic performance measures, we also interpreted changes in exploitable biomass and egg production as relative indicators for the stock. Among the simulated procedures, we found that important opportunities for large increases in profitability may be achieved through fleet-size reductions, whereas harvest quotas did relatively little to improve economic gains. Specifically for the SGPF, a November closure, or a June closure plus an increase in the pre-Christmas catch cap also appeared to result in good overall performance, and would be relatively straightforward and cost-effective to implement (financing the removal of vessels was not included in the simulations). Whilst there was no evidence to suggest that quota was the best way forward for either fishery from the management procedures tested, this study does not fully explore the potential benefits of introducing quota management arrangements. Any changes to the specifications of these management procedures should therefore be separately evaluated.

This study is a first for WKP and, as such, is a pilot for further development. Although the best available data were used in the development of the model, the main limitation of the data was the truncated series of standardised catch rates (1991—2013) used to define the stock-recruitment relationship. There was a notable lack of contrast in these data (particularly for the SGPF), and while this may be symptomatic of a well-managed fishery, it also means that model outputs, including reference points for MSY and MEY, tend to be less certain. Further analyses may be worthwhile to explore the possibility of including pre-1991 catch rates and thereby provide additional contrast for a more accurate representation of abundance and fishing mortality through time.

Biennial updates of the model may be appropriate for a short-lived species such as the WKP, as well as providing opportunity to address the following identified research and model-development needs:

- Explore alternative methods for generating size-transition matrices that will enable the simultaneous fitting of the model to catch rate and size composition data (unlike the two-stage approach required in this project);
- Undertaking a purpose-designed survey to provide better estimates of exploitable biomass;
- Conducting further sensitivity analyses for some assumed parameters (e.g. instantaneous natural mortality);
- Improving the accuracy and representativeness of the economic data; and
- Comparing model outputs with those using another model (e.g. delay-difference model).

Although further development of a newly-developed model is inevitable, the results presented are considered real-life examples of how the model can contribute towards greater profitability for the GSVPF and SGPF in the future. For the first time, model-derived reference points for MSY and MEY were estimated and management strategies evaluated. The project's outputs can be considered in the future stock assessment and development of harvest strategies for both fisheries. To increase the likelihood of adoption in the SGPF, PIRSA Fisheries and Aquaculture, SARDI Aquatic Sciences and industry have recently agreed on a stock assessment development program over the next few years, in which the bio-economic model will comprise one of the tools available to assist with the program.

KEYWORDS: Western King Prawn, *Penaeus (Melicertus) latisulcatus*, fishery economics, management strategy evaluation, MSE, maximum sustainable yield, MSY, maximum economic yield, MEY, generalised linear model, GLM.

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1 Introduction

Many fisheries in Australia are facing the significant challenge of reversing declines in profits as a result of the economic climate in which they operate. These worrying trends have prompted fisheries management agencies and affected stakeholders to shift their focus towards objectives of profitability, such as maximum economic yield (MEY), rather than promoting maximum sustainable yield (MSY). The Gulf St Vincent Prawn Fishery (GSVPF) and Spencer Gulf Prawn Fishery (SGPF) of South Australia are two such fisheries in which profits and general economic performance in recent years have become a concern. Declines in profit have been attributed to an increased supply of aquaculture-farmed prawns on domestic and international markets, appreciating Australian dollar, increasing fuel prices and, for the GSVPF, over-capitalisation, and are exacerbated during years of low catch rates.

The separately-managed GSVPF and SGPF are the only substantial prawn fisheries in Australia that exclusively target a single species, i.e. the Western King Prawn (WKP, *Penaeus (Melicertus) latisulcatus*)[1]. The SGPF is the larger of the two fisheries, and is restricted to 39 active licences that harvest ~2000 t of WKP annually at a landed value of $30 million, whereas the GSVPF is comprised of 10 licences, with landings of ~200 t valued at $2-3 million. Both fisheries use demersal otter trawl gear of similar configuration, and are permitted to also land two species/groups as by-product, Southern Calamari (*Sepioteuthis australis*) and scyllarid lobsters (*Ibacus* spp.). Trawling occurs in November, December and March–June around the new moon (between the last and first quarter phases, when catch rates are highest). Traditionally, the fleet in each fishery operates as one (i.e. fishing the same nights), and thus individual licences essentially operate under a competitive quota system. In recent years, annual effort has averaged 26 and 51 nights per vessel in the GSVPF and SGPF, respectively, which are only fractions of historic levels.

Reference points are a key requirement for indicating the stock status of any fishery, and these can be based on measures (or performance indicators) such as catch rates or model estimates of biomass. Their development is often complex, relying on numerical analyses of data that are accurate and from sufficiently long time series to serve as an index for population abundance (Hilborn, 2002). Model-based reference points such as MSY and the corresponding fishing effort for MSY (E_{MSY}) have been reported for many prawn fisheries in Australia (Dichmont *et al.*, 2001; O'Neill *et al.*, 2005; O'Neill and Turnbull, 2006). Empirical reference points are data-based rather than model-based, and have been used in prawn fisheries for status reporting (e.g. Rowling *et al.*, 2010; Fisheries Queensland, 2013) and in harvest strategies and decision rules for management (e.g. Department of Fisheries Western Australia, 2014). The GSVPF and SGPF are examples of the latter, where fishery-independent survey catch rates and prawn size have historically been used to adaptively determine the area that is subsequently opened to fishing (Dixon and Sloan, 2007; PIRSA, 2014). During fishing, fleet catches are monitored, and decisions are made to restrict the number of nights if the average catch rate drops below acceptable levels and/or adjust the area if prawn size criteria are not met. Whilst these empirical reference points appear to have been useful for guiding management in the past to address the objective of biological sustainability, they have not been validated against model-based reference points, and so it is difficult to know how closely they actually relate to sustainable stock levels or the fisheries' economics.

The economic situations of both fisheries have prompted the need for change. The GSVPF has been subject to several independent reviews over its history, including three reviews in the last four years (Knuckey *et al.*, 2011; Morgan and Cartwright, 2013; Dichmont, 2014) on stock assessment, economic performance, and management framework. Their terms of reference varied, but all of these reviews took place during a period in which there was protracted poor economic performance of the fishery and therefore greater scrutiny of management and research. These reviews found that management and stock

[1] A third WKP fishery exists in South Australia, the West Coast Prawn Fishery (WCPF). The WCPF is quite different to the GSVPF and SGPF in that it is an oceanic and relatively small-scale and data-poor fishery. For these reasons, this project focused on the gulf fisheries.

assessment of the GSVPF were sound, but there were probably too many vessels for the fishery to be economically viable. Negative returns on investment have been estimated for most of the past 10 years (EconSearch, 2013), and in the 2013 fishing year, the fishery was closed, primarily due to continued poor economic performance and the need to develop management arrangements that would promote the necessary restructure of the fishery.

The SGPF has been recognised by the Food and Agricultural Organization (FAO) of the United Nations as one of the best managed prawn fisheries in the world (Gillett, 2008), and in 2011 became the first prawn fishery in the South-Pacific to be accredited by the Marine Stewardship Council (MSC) for its ecologically sustainable fishing practices. However, despite these accolades, the SGPF has also experienced a downward turn in economic performance. Consequently, the Spencer Gulf and West Coast Prawn Fishermen's Association (SGWCPFA) held workshops with licence holders and set up a subcommittee to investigate the need for economic reform. Among the licence holders, there was general agreement that the profitability of businesses had declined over the past 10 years, but there were different views on what options should be pursued to improve their economic situation (S. Clark, Executive Officer, SGWCPFA, personal communication).

The use of vessel-based economics to calculate MEY as the preferred objective to MSY was first introduced into fisheries policy in Australia in 2007 for Australia's Commonwealth fisheries (Australian Government, 2007). This has been applied to the multi-species and multi-stock Northern Prawn Fishery (NPF) across tropical waters of northern Australia (Punt *et al.*, 2010) and, recently, the Eastern King Prawn (EKP, *M. plebejus*) of the East Coast Otter Trawl Fishery (ECOTF) in subtropical waters of New South Wales and Queensland (O'Neill *et al.*, 2014). In South Australia, bio-economic decision-support model outputs including MEY have been developed for evaluating management strategies in southern rock lobster fisheries of South Australia and neighbouring jurisdictions (McGarvey *et al.*, 2014).

In this study, the first bio-economic model was developed for the WKP fisheries in South Australia. The model is based on the work of O'Neill *et al.* (2014) for the EKP, and is the most comprehensive attempt thus far to integrate WKP population dynamics and vessel-based economic data in the GSVPF and SGPF. Example outputs of the model are presented, and include estimates of MSY and MEY reference points and bio-economic evaluation of a range of simulated 'government-stakeholder' management procedures. Both sets of outputs will help determine the status of the GSVPF and SGPF explicitly in terms of MSY and MEY and a path to a more profitable future. In an overall context, this study contributes to the management, use and development of the WKP resource in a manner that is consistent with ecologically sustainable development, which has become part of fisheries legislation in South Australia (*Fisheries Management Act 2007*).

2 Need

In recent years, Australian wild catch prawn fisheries have had to compete with increased importation of cheap aquaculture prawns. This along with other economic conditions of increasing costs of fishing and static prawn prices have reduced profitability for domestic prawn fisheries (e.g. Punt *et al.*, 2010; O'Neill *et al.*, 2014). Given the reported declines in profitability, there is now an important need to examine approaches to improve catch rates and fishing profit.

South Australia has single-species prawn fisheries in Spencer Gulf and Gulf St Vincent that target the WKP. Both fisheries have management plans that include a detailed harvest strategy to guide fishing activities and performance indicators for fishery assessment. While there are performance indicators to assess overall economics, fishing effort is not set to achieve optimal economic performance.

The GSVPF has recently undergone an independent review process, in which bio-economic modelling was identified as the highest research priority for the fishery. Consequently, the Saint Vincent's Gulf Prawn Boat Owners' Association (SVGPBOA) endorsed the proposal for this project. Similarily, the Spencer Gulf and West Coast Prawn Fishermen's Association (SGWCPFA) endorsed the development of a bio-economic model as a high priority for the SGPF.

3 Objectives

1. Collate and analyse available data for the Gulf St Vincent and Spencer Gulf prawn fisheries for integration into a bio-economic model.
2. Modify the existing Eastern King Prawn bio-economic model to fit the Gulf St Vincent and Spencer Gulf prawn fisheries data.
3. Determine economically optimal fishing strategies for the Gulf St Vincent and Spencer Gulf prawn fisheries.
4. Develop an approach to incorporate optimal fishing strategies into the harvest strategy for each fishery.
5. Provide extension of the developed model and its outputs to stakeholders of other Australian prawn trawl fisheries.

4 Methods

4.1 Input data

4.1.1 Overview

The input data for the WKP bio-economic model is comprehensive. For both the GSVPF and SGPF (Figure 4.1), these data comprise: 1) nominal catch and effort since the inception of the fisheries almost 50 years ago; 2) standardisation of more than 20 years of these catches; 3) exploitable biomass estimates, size composition, length at recruitment, and other biological relationships derived from almost a decade of fishery-independent surveys; 4) estimates of growth from several years of tag-recapture studies; 5) prawn landing prices and other economic parameters; and 6) a range of management procedures for simulation (Table 4.1).

For each fishery, all data were collated, entered and stored in worksheets in a single Microsoft Excel file. This facilitated convenient reading of the data into the bio-economic model and the transparent format allowed for easy modification of inputs.

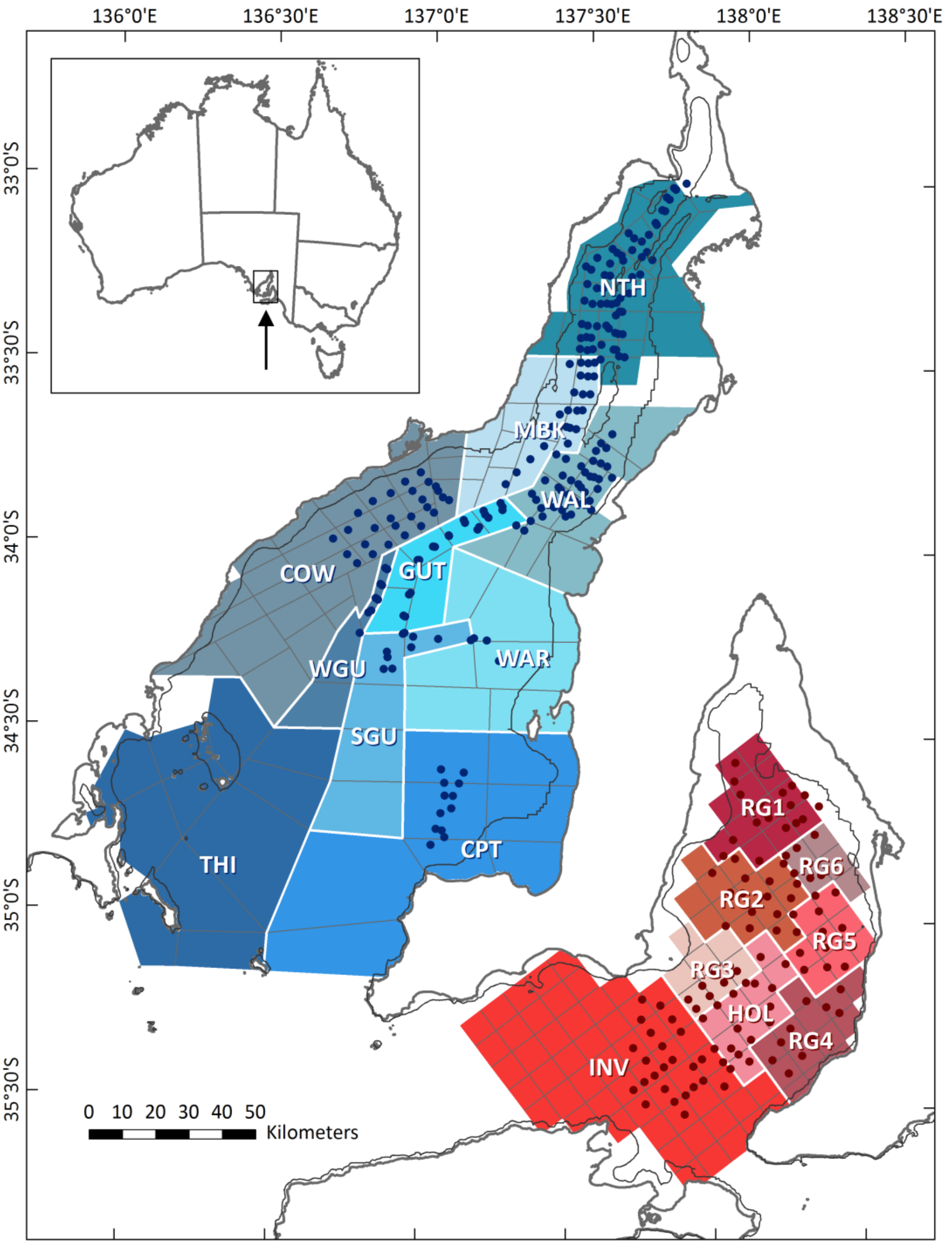

Figure 4.1. Map of South Australia's GSVPF (shaded red) and SGPF (shaded blue) showing the fishing blocks (small polygons), regions (large shaded polygons), survey shot locations (dots) and 10-m depth contour that separates the fishable area (≥10 m) and prohibited area to trawling (<10 m). Region abbreviations: COW, Cowell; CPT, Corny Point; GUT, the 'Gutter'; HOL, the 'Hole'; INV, Investigator Strait; MBK, Middlebank; NTH, North; RG1, Region 1; RG2, Region 2; RG3, Region 3; RG4, Region 4; RG5, Region 5; RG6, Region 6; SGU, South Gutter; THI, Thistle; WAL, Wallaroo; WAR, Wardang; WGU, West Gutter.

Table 4.1. Input data, data sources and worksheets for the WKP bio-economic model.

Worksheet	Data	Source	Notes	References
'cpue'	Nominal catch and effort	Fishery-dependent (FD) data from: 1) South Australian Fishing Industry Council (SAFIC) records (fishing years 1968—1990); and 2) commercial logbooks (fishing years 1991—2013).	Data were aggregated by month t = 1…540 (corresponding to Oct 1968—Sep 2013), and also labelled with actual year/month and fishing year/month. Other monthly data were similarly organised and identifiable by time step t.	
	Standardised catch rates (fishery and survey)	1) FD commercial logbooks (fishing years 1991-2013); 2) fishery-independent (FI) surveys (GSVPF: Dec, Mar, Apr, May in fishing years 2005—2012; SGPF: Nov, Feb, Apr in fishing years 2005—2013); and 3) environmental factors (BOM, 2014; USNO, 2014).	Generalised linear models were used to standardise catch rate corresponding to kg block-vessel-night^{-1} (fishery) and kg trawl-shot^{-1} (survey).	
	Survey exploitable biomass estimates	FI surveys (same surveys used for standardising catch)	Exploitable biomass was estimated by extrapolating survey catch rates to the fishable area of the gulf and correcting for the fraction of WKP assumed to be retained in the trawl net.	
'lf'	Length frequency (carapace length 1…75 mm)	FI surveys (same surveys used for standardising catch)	The length-frequency distribution for each survey was made up of samples from 112 locations in Gulf St Vincent (GSV) and up to 209 locations in Spencer Gulf (SG) (Figure 4.1), with ~100 prawns collected at each location.	
'lfrec'	Recruitment at length	FI survey (SGPF, Feb 2007, males)	A Gaussian mixture model in Matlab® was fitted to survey length-frequency data to partition the first normal density component, from which posterior probabilities (of recruitment) were assigned to each 1-mm length class.	
'stm_male'	Size-transition matrix (males)	Tag-recapture studies (GSV: Dec 1988—Nov 1996; SG: Oct 1984—Jun 1991)	Tag-recapture data were analysed using a seasonal von Bertalanffy growth model to generate male and female size-transition matrices for each gulf (0).	Xiao (1999); Xiao (2000); Xiao and McShane (2000b); Carrick and Ostendorf (2005); Carrick (2003); Chen *et al.* (2003)
'stm_female'	Size-transition matrix (females)	*Same as for 'stm_male'*		

Worksheet	Data	Source	Notes	References
'bio'	Biological schedule parameter values and errors	Various	Includes estimates for natural mortality *M* (month^{-1}), maturity at length (females), fecundity, spawning pattern, weight at length (males and females), catch per unit effort (CPUE) unit conversion scalars, parameter bounds and distributions, and first year for estimating recruitment.	Hall and Watson (2000); Xiao and McShane (2000a); Carrick (2003); Noell *et al.* (2014 and references therein); O'Neill *et al.* (2014)
'grades'	Frequency of harvest by size-grade category	FD commercial logbooks (GSV: fishing years 2007—2012; SG: fishing years 2003—2013)	Size-grade categories: 1) small (>20 prawns lb^{-1}); 2) medium (16-20 lb^{-1}); 3) large (10-15 lb^{-1}); and 4) extra-large (<10 lb^{-1}).	
'grade_cat'	Size-grade category at length	FI surveys (length-weight relationships) and market grade/category information.	Size-grade category at length determined by: 1) weight at length; 2) the number of prawns per pound; then 3) re-categorisation by length (there was no difference in category at length between males and females).	Carrick (2003)
'econ'	Economic parameter values	Most recent economic surveys conducted by EconSearch (2007/08 for GSVPF; 2012/13 for SGPF).	2007/08 data for GSVPF were adjusted to 2011/12 based on annual changes in effort, price from input suppliers and consumer price index (CPI).	EconSearch (2009); EconSearch (2014).
'mp'	Management procedures	Discussions with industry and management.	Developed in consultation with PIRSA Fisheries and Aquaculture and industry representatives.	
'tac_xmas'	Pre-Christmas catch cap schedule	November FI surveys (mean catch rate of adult prawns)	Pre-Christmas (November—December) harvest decision rules for the SGPF.	PIRSA (2014)
'value'	Monthly landing price by length/grade	Industry co-operative.	Based on 2013/14 prices.	

(continued)

4.1.2 Commercial harvest data

Historical harvests of WKP by the GSVPF and SGPF date back to fishing year 1969 (Figure 4.2; Figure 4.3). A fishing year was defined as the 12-month period from October (fishing month 1) to September (fishing month 12) and labeled according to the following calendar year of this period (e.g. October 2012—September 2013 = fishing year '2013').

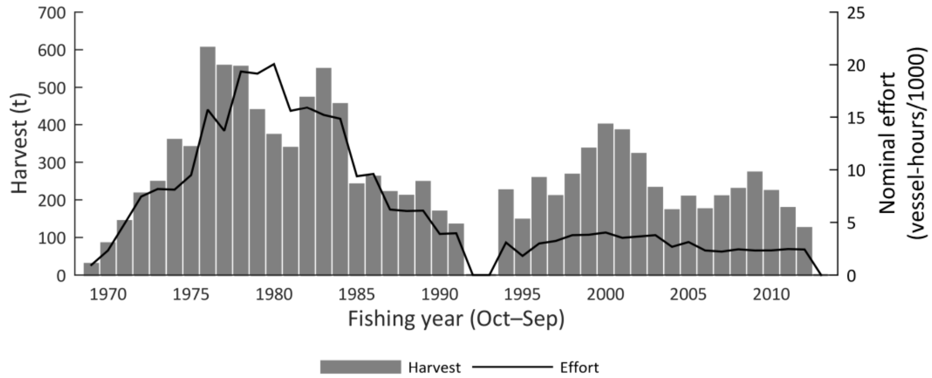

Figure 4.2. Annual harvest and effort of WKP by the GSVPF from 1968—2013.

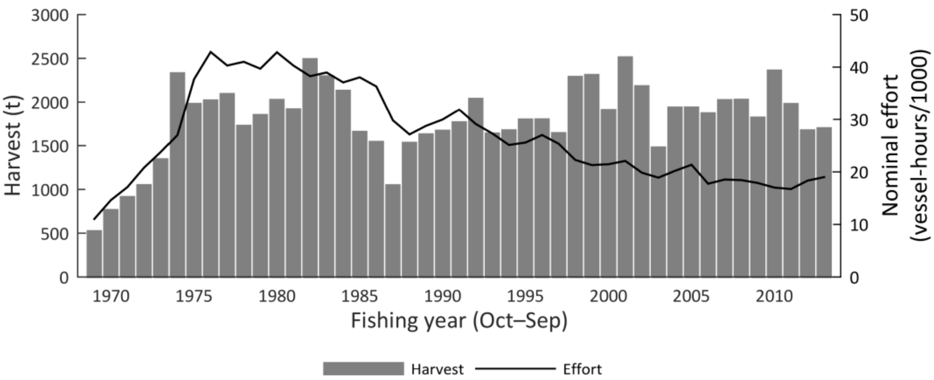

Figure 4.3. Annual harvest and effort of WKP by the SGPF from 1968—2013.

Monthly harvests and effort for fishing years 1969—2013 were reconstructed from: i) South Australian Fishing Industry Council (SAFIC) annual records from 1968—1972 (calendar years); ii) SAFIC monthly records from January 1973—September 1990; and iii) whole-fleet compulsory daily commercial logbooks from October 1990—September 2013. The GSVPF totals include the harvests from Investigator Strait between 1976 and 1987 when this region was fished under jurisdiction of the Australian Government. The GSVPF was closed in fishing years 1992, 1993 and 2013[2].

Annual harvests and effort from 1968—1972 were disaggregated to month by assuming the same average proportions as 1973—1977. SAFIC records for fishing years 1989 and 1990 were provided by fishing period, so where a period did not fall within a calendar month, monthly harvests and effort were estimated based on the proportion of nights fished in that month. Daily catch and effort estimates were recorded by each licence holder (or skipper) for each commercial fishing block fished (Figure 4.1). These estimates were subsequently validated and adjusted according to monthly unloading logbooks, then aggregated by month.

[2] During the current project, a decision was made to extend the 2013 closure of the GSVPF for another year (i.e. 2014).

4.1.3 Standardised commercial catch rates

Catch rate analyses were conducted on daily logbook data from fishing years 1991—2013, aggregated to catch (kg block-vessel-night^{-1}). The logbook database prior to 1991 was incomplete, particularly by block and vessel, and therefore was not included in the standardisation.

Generalised linear modelling (GLM; Nelder and Wedderburn, 1972) is the most common method for standardising catch and effort data from fisheries (Maunder and Punt, 2004), and was applied to the GSVPF and SGPF, with all analyses performed using the R programming language (R Core Team, 2013). Box-Cox transformation (Box and Cox, 1964) and diagnostic plots indicated that, among different distributional assumptions tested, a Gaussian normal error distribution and identity link fitted to cube root transformed catches were appropriate. The analyses included fixed terms ($\mathbf{X\beta}$), and followed the terminology and notation of O'Neill *et al.* (2014). Where data ($\mathbf{X_1}$, $\mathbf{X_2}$, $\mathbf{X_3}$, $\mathbf{X_4}$, $\mathbf{X_5}$, $\mathbf{X_6}$, $\mathbf{X_7}$) were relevant and available, the models were fitted to estimate the following parameter effects:

- Scalar model intercept $\boldsymbol{\beta_0}$;
- Abundance $\boldsymbol{\beta_1}$ for data $\mathbf{X_1}$ (fishing year-month combined factor);
- Region $\boldsymbol{\beta_2}$ for data $\mathbf{X_2}$ (amalgamation of fishing blocks; 6 regions in GSVPF, 10 regions in SGPF) (Figure 4.1);
- Vessel $\boldsymbol{\beta_3}$ for data $\mathbf{X_3}$ (identified by licence number; 10 licences in GSVPF, 39 licences in SGPF);
- Lunar phase $\boldsymbol{\beta_4}$ for data $\mathbf{X_4}$ (fraction of the moon illuminated at midnight for Chamorro, which is equivalent to AEST; USNO, 2014);
- Lunar phase (lagged) $\boldsymbol{\beta_5}$ for data $\mathbf{X_5}$ (lunar phase shifted ¼ phase; only considered when the primary variable $\boldsymbol{\beta_4}$ was significant);
- Cloud cover $\boldsymbol{\beta_6}$ for data $\mathbf{X_6}$ (mean fraction from three-hourly readings, measured in eighths, between 1800 and 0600 hours; BOM, 2014); and
- Fishing effort $\boldsymbol{\beta_7}$ for data $\mathbf{X_7}$ (hours, cube root transformed).

The most parsimonious model (Table 4.2; Table 4.3) was obtained using a stepwise removal procedure; firstly by determining the generalised variance inflation factor (GVIF; Fox and Monette, 1992) and removing terms causing collinearity (as indicated by $\mathrm{GVIF}^{1/(2\mathrm{df})}$ values > 2), and secondly, by removing non-significant terms in analysis of deviance (type II method; PIRSA, 2014) according to the *F* statistic.

Table 4.2. Final GLM used to standardise commercial catch rates in the GSVPF from 1991—2013.

Response:	(kg block-vessel-night^{-1})$^{1/3}$
Fixed terms:	$\boldsymbol{\beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + X_4\beta_4 + X_5\beta_5 + X_6\beta_6 + X_7\beta_7}$
Predictions:	$\boldsymbol{\beta_1}$

Table 4.3. Final GLM used to standardise commercial catch rates in the SGPF from 1991—2013.

Response:	(kg block-vessel-night^{-1})$^{1/3}$
Fixed terms:	$\boldsymbol{\beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + X_4\beta_4 + X_5\beta_5 + X_7\beta_7}$
Predictions:	$\boldsymbol{\beta_1}$

Analyses also included a check for a change in fleet 'fishing power'. Vessel proportions were multiplied by their coefficients ($\mathbf{X_3}$), summing the products for each year, raising to the power of 3 (to be on the untransformed scale), and dividing each year by the first year. The relatively flat annual trend suggested there has been little change in fishing power since 1991 for either fishery.

The 'effects' package in R was used to determine predicted means for the main effects of the model (e.g. year-month) by setting other numeric variables to their mean values (except effort, which was specified), and by setting factors to their proportional distribution in the data by averaging over contrasts (Fox, 2003; Fox and Hong, 2009). Effort had a multimodal distribution (four modes), so the cubic-root of the mean of the largest two modes (as determined by the R package 'mixdist', Macdonald and Du, 2012) was used to represent typical effort per block per vessel-night in the fleet. As the predicted means were on the transformed scale, the cubic-root bias correction $\mu^3 + 3\mu\sigma^2$ was necessary to back-transform to their original scale (Kendall *et al.*, 1983), where μ is the predicted mean on the transformed scale, and σ^2 is the model variance.

4.1.4 Standardised survey catch rates

Independent surveys of abundance were conducted in GSV in December, March, April and May of fishing years 2005—2012 (except 2012, when only April and May surveys were conducted) and SG in November, February and April of fishing years 2005—2013 (e.g. Dixon *et al.*, 2012; Noell *et al.*, 2014). Using commercial vessels and trawl nets, the surveys monitored catch rates and prawn size at fixed locations (up to 112 samples for GSV and 209 samples for SG) within most regions near the beginning, middle and end of the fishing season. In addition to providing an index of relative abundance, these surveys are also used to determine the area to be subsequently fished based on decision rules involving catch rate and size criteria.

As for commercial catch rates, individual survey catches (adjusted to two nets where necessary) were analysed using a Gaussian GLM with cubic-root transformation and identity link, except effort (cubic-root transformed) was inserted as an offset (0). Survey catch (kg trawl-shot^{-1}) was predicted for the fishing year-survey (month) combined factor with the explanatory factors of region, vessel and, for SG, tide direction (relative to vessel, i.e. against tide, with tide or slack tide). Where necessary, predicted mean catch was also expressed in kg h^{-1} and lb min^{-1} for industry reporting needs.

4.1.5 Size composition data

Two datasets on size structure were available: 1) carapace-length (CL) frequencies from surveys conducted since 2005; and 2) whole-fleet logbook size-grade frequencies obtained from 2007—2012 for the GSVPF, and 2003—2013 for the SGPF. Together, these two datasets were used to quantify monthly changes in WKP size.

Carapace-length frequencies were recorded routinely by observers at each survey location. Each prawn was sexed and measured to 1-mm length classes. Grading categories classified prawn size by the number of prawns per pound (heads-on and sexes combined). Size-grade frequencies comprised four categories: 1) >20 lb^{-1} (small) ≈ 1-34 mm CL; 2) 16-20 lb^{-1} (medium) ≈ 35-38 mm; 3) 10-15 lb^{-1} (large) ≈ 39-45 mm; and 4) <10 lb^{-1} (extra-large) ≈ 46-75 mm. 'Soft and broken,' an additional category, were infrequent and not analysed. No independent data were available to assess the accuracy of the at-sea commercial size grading, but the same data were acceptable to processors to determine price paid to fishers. Larger prawns fetched a higher price for the same weight.

4.1.6 Size-transition matrices

Prawn tag-recapture data obtained from December 1988 to November 1996 for GSV (Xiao and McShane, 2000b) and October 1984 to June 1991 from SG (Carrick and Ostendorf, 2005) were fitted to a seasonal von Bertalanffy growth model, and sex-specific size-transition matrices for each gulf were generated following the methods described in Appendix C. Assuming a normal probability density function, the transition matrices allocated a proportion of WKP in carapace length-class l' at time t – 1 to grow into a new length l over one time-step t, where t represents one month.

4.1.7 Economic data

Monthly WKP landing prices by size grade for the 2013/14 financial year were sourced from an industry co-operative, which represents approximately half of the SGPF licences, and an Adelaide processor, which represents one out of ten GSVPF licences. Price data were available for seven size grades, which were re-categorised by carapace length: 1) 31-40 lb^{-1} ≈ 28-30 mm; 2) 21-30 lb^{-1} ≈ 31-34 mm; 3) 16-20 lb^{-1} ≈ 35-38 mm; 4) 10-15 lb^{-1} ≈ 39-45 mm; 5) 8-10 lb^{-1} ≈ 46-49 mm; 6) 6-8 lb^{-1} ≈ 50-54 mm; and 7) <6 lb^{-1} ≈ 55-75 mm. Monthly landing prices used for the model were based on industry information that the demand is greater for raw prawns between January and October and cooked prawns in November and December, and a higher price is paid for cooked prawns (Table 4.4; Figure 4.4).

Table 4.4. Monthly WKP landing prices ($ kg^{-1}) by size grade and product type.

Size grade (lb^{-1})	Carapace length (mm)	Carton size	Price (AU$ kg^{-1})					
			Raw		Cooked		Estimated mix (raw : cooked)	
			Nov/Dec	Other months	Nov/Dec	Other months	Nov/Dec (5 : 95)	Other (80 : 20)
31-40	28-30	10 kg	11.00	7.50	12.00	8.50	11.95	7.70
21-30	31-34	10 kg	12.50	9.50	13.50	10.50	13.45	9.70
16-20	35-38	10 kg	17.00	12.50	18.00	13.50	17.95	12.70
11-15	39-45	10 kg	19.00	14.50	20.00	15.50	19.95	14.70
8-10	46-49	5 kg	22.00	18.25	23.50	19.75	23.43	18.55
6-8	50-54	5 kg	24.25	20.25	25.75	21.75	25.68	20.55
<6	55-75	5 kg	26.00	24.00	27.50	25.50	26.30	24.30

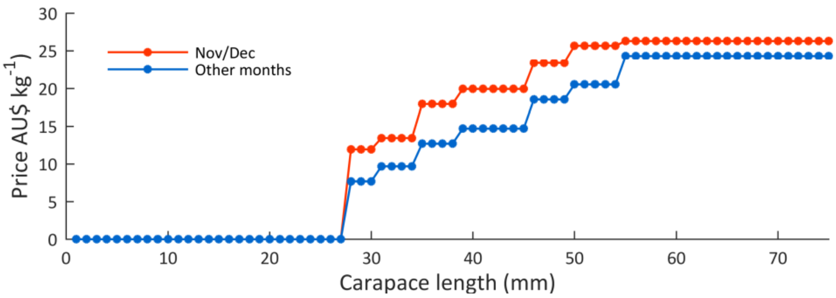

Figure 4.4. 2013/14 monthly WKP landing prices ($ kg^{-1}) by carapace length based on estimated proportions of raw and cooked prawns in demand.

The average combined by-product value for scyllarid lobsters and Southern Calamari was calculated from logbook harvests and price data from processors and licence holders (Table 4.5; Table 4.6).

Economic parameters were based on survey responses from 4 (40%) GSVPF licence holders and 22 (56%) SGPF licence holders. Parameter values (means) were estimated for the 2011/12 financial year for the GSVPF and 2012/13 for the SGPF (EconSearch, 2014) (Table 4.5; Table 4.6). The most recent economic survey for the GSVPF was conducted in 2007/08 (EconSearch, 2009). Values were therefore adjusted to 2011/12 based on annual changes in fishing effort, price from input suppliers (e.g. fuel) and the consumer price index (CPI) for Adelaide (EconSearch, 2010; 2011; unpublished data). Vessel and fuel costs were also estimated for notional higher levels of fishing power expected with a reduction in the number of vessels, while all other economic parameters were held constant (Table 4.5; Table 4.6).

A coefficient of variation (CV) of 10% was estimated for variable costs and annual fixed costs. We applied the same interest rate (5.0%), opportunity cost of capital (assumed to equal interest rate) and economic depreciation rate (3.7%) as the Commonwealth's Northern Prawn Fishery (Punt *et al.*, 2010) (Table 4.5; Table 4.6).

Table 4.5. Input parameter values for the GSVPF economic model at different levels of fishing power. Bullets (•) indicate no change from 2011/12 fishing power (f_{pr} = 1.00).

Parameters	**Fishing power (f_{pr}; proportion)**		
	1.00	**1.05**	**1.10**
Fleet vessel type			
Vessel size (v_S; mean)	19.1	20.8	21.6
Number of vessels (V_y)	10	7	5
Variable costs			
Labour (c_L; proportion)	0.40	•	•
Packaging (c_M; \$ kg^{-1})	0.30	•	•
Repairs (c_K; \$ vessel-night^{-1})	550	•	•
Fuel (c_F; \$ vessel-night^{-1})	1549	1626	1704
Incidentals (c_O; \$ vessel-night^{-1})	46	•	•
Coefficient of variation (cv_c)	*0.1*	•	•
Annual fixed costs			
Vessel (W_y; \$ vessel-year^{-1})	89432	93904	98375
Investment (K_y; \$ vessel-year^{-1})	1171493	•	•
WKP (ρ; proportion)	1	•	•
Other (f_O; \$ vessel-year^{-1})	0	•	•
Coefficient of variation (cv_f)	*0.1*	•	•
Revenue			
By-product ($\bar{B}^{by}$; \$ vessel-night^{-1})	89	•	•
Coefficient of variation (cv_{by})	*0.21*	•	•
Annual economic rates			
Interest (i; proportion)	0.05	•	•
Opportunity ($o = i$; proportion)	0.05	•	•
Depreciation (d; proportion)	0.037	•	•

Table 4.6. Input parameter values for the SGPF economic model at different levels of fishing power. Bullets (•) indicate no change from 2012/13 fishing power (f_{pr} = 1.00).

Parameters	Fishing power (f_{pr}; proportion)				
	1.00	**1.05**	**1.10**	**1.15**	**1.20**
Fleet vessel type					
Vessel size (v_S; mean)	21.2	21.7	21.9	22.0	22.0
Number of vessels (V_y)	39	33	30	20	12
Variable costs					
Labour (c_L; proportion)	0.44	•	•	•	•
Packaging (c_M; \$ kg^{-1})	0.30	•	•	•	•
Repairs (c_K; \$ vessel-night^{-1})	907	•	•	•	•
Fuel (c_F; \$ vessel-night^{-1})	1505	1580	1656	1731	1806
Incidentals (c_O; \$ vessel-night^{-1})	234	•	•	•	•
Coefficient of variation (cv_c)	*0.1*	•	•	•	•
Annual fixed costs					
Vessel (W_y; \$ vessel-year^{-1})	88794	93234	97673	102113	106553
Investment (K_y; \$ vessel-year^{-1})	1045520	•	•	•	•
WKP (ρ; proportion)	1	•	•	•	•
Other (f_O; \$ vessel-year^{-1})	0	•	•	•	•
Coefficient of variation (cv_f)	*0.1*	•	•	•	•
Revenue					
By-product ($\overline{B}^{by}$; \$ vessel-night^{-1})	118	•	•	•	•
Coefficient of variation (cv_{by})	*0.15*	•	•	•	•
Annual economic rates					
Interest (i; proportion)	0.05	•	•	•	•
Opportunity (o = i; proportion)	0.05	•	•	•	•
Depreciation (d; proportion)	0.037	•	•	•	•

4.2 Bio-economic model

4.2.1 Modelling flow

The prawn bio-economic model was developed using Matlab® (MathWorks, 2014). The model was run in two phases: i) historical estimation of the WKP stock from 1968 to 2013; and ii) simulations of WKP parameter values and uncertainty to evaluate reference points and management procedures. The flow of operations and source Matlab files are summarised in Figure 4.5.

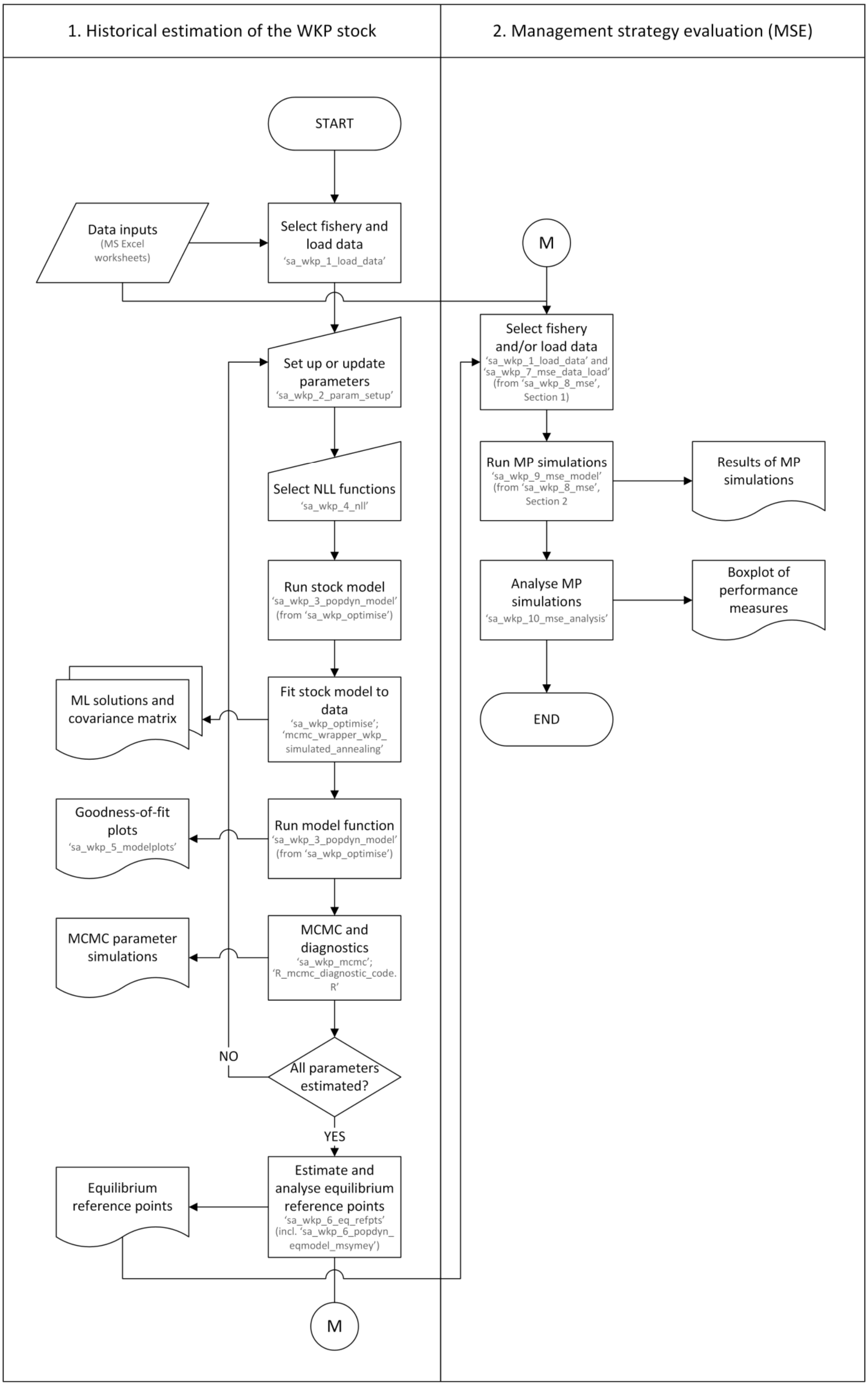

Figure 4.5. Flow of operations and source files for the WKP bio-economic model. Abbreviations: NLL, negative log-likelihood; ML, maximum likelihood; MCMC, Markov Chain Monte Carlo; MP, management procedure.

4.2.2 Population dynamic model

The population dynamic model for WKP in the GSVPF and SGPF was based on that developed for the Eastern King Prawn (EKP, *M. plebejus*) fishery in Queensland and New South Wales (O'Neill *et al.*, 2014). The model operated at a monthly time step and tracked numbers (N) and biomass (B) of prawns by their sex (s) and length (l) (Table 4.7; Table 4.8), and included the processes of mortality, growth and recruitment in every month (t).

Table 4.7. Equations used for simulating WKP population dynamics (see Table 4.8 for notation).

Monthly population dynamics	Equation
Number of prawns: $N_{l,t,s} = \exp(-M)\sum_{l'} \Xi_{l,l',t-1,s}\left(1 - v_{l'}u_{t-1}\right)N_{l',t-1,s} + 0.5R_{l,t}$	(1)
Recruitment number — Beverton-Holt formulation: $R_{l,t} = \dfrac{E_{y-1}}{\alpha + \beta E_{y-1}}\exp(\eta_y)\phi_t \Lambda_l$, where y indicates the fishing year.	(2)
Spawning index — annual number of eggs: $E_y = \sum_t \sum_l N_{l,t,s} m_l f_l$, where s = female.	(3)
Recruitment pattern — normalised monthly proportions (modes 1 and 2): $\phi_t^1 = \exp\left\{\kappa \cos\left[2\pi(t-\mu_1)/12\right]\right\} \Big/ \sum_{t=1}^{12} \exp\left\{\kappa \cos\left[2\pi(t'-\mu_1)/12\right]\right\}$ $\phi_t^2 = \exp\left\{\kappa \cos\left[2\pi(t-\mu_2)/12\right]\right\} \Big/ \sum_{t=1}^{12} \exp\left\{\kappa \cos\left[2\pi(t'-\mu_2)/12\right]\right\}$ $\phi_t = \phi_t^1 \tau + \phi_t^2 (1-\tau)$, where t indicates fishing month 1…12. $\tau = \exp(\varphi) \Big/ \left[1 + \exp(\varphi)\right]$, where τ is the mixing proportion of seasonal recruitment distributions 1 and 2 based on a logit transformation. The mixing parameter τ was tested to explore a bimodal recruitment pattern but was not used in final analyses.	(4)
Mid-month exploitable biomasses — forms 1 and 2: $B_t^1 = \sum_l \sum_s N_{l,t,s} w_{l,s} v_l^{\mathrm{f}} \exp(-M/2)$ $B_t^2 = \sum_l \sum_s N_{l,t,s} w_{l,s} v_l^{\mathrm{f}} \exp(-M/2)(1-u_t/2)$, where f indicates fishery (form 1) or survey (form 2) vulnerability.	(5)
Harvest rate: $u_t = C_t \big/ B_t^1$, where C is the monthly harvest (kg).	(6)
Prawn vulnerability to fishing gear: $v_l^{\mathrm{f}} = 1 \Big/ \left\{1 + \exp\left[\delta_{\mathrm{f}}\left(l_{\mathrm{f}}^{50} - l\right)\right]\right\}$, where f indicates different selectivity between fishery and survey.	(7)
Catch rates: Fishery (f; kg block-vessel-night^{-1}): $c_t^{\mathrm{f}} = q^{\mathrm{f}}(t) B_t^2$, where f = fishery. Survey (s; kg trawl-shot^{-1}): $c_t^{\mathrm{f}} = q^{\mathrm{f}} B_t^1$, where f = survey.	(8)

Table 4.8. Definitions and values for the WKP population model parameters.

Model parameters	Equations, values and errors	Notes
Fixed		The values and errors were calculated from published research or data.
Ξ	See Table E.7 and Table E.8 for parameter values for Eq. (6) in Appendix C.	Tag-recapture data were analysed using a seasonal von Bertalanffy growth model to generate male and female size-transition matrices (0). The size-transition matrix allocated a proportion of WKP in carapace length-class l' at time t-1 to grow into a new length class l over one monthly time step t. The transitions varied with prawn sex s and month t. Based on the growth model, a decline in the variance of the growth increment was assumed with increasing l.
Λ	Summary percentiles [2.5 25 50 75 97.5] = 13.8, 19.2, 22.0, 24.8 and 30.2 mm.	Proportion of WKP recruitment in length class l (1…75 mm). In Statistics Toolbox™ for Matlab, Gaussian mixture models were fitted to survey length-frequency data using an expectation maximisation algorithm, which assigns posterior probabilities to each component density with respect to each observation (McLachlan and Peel, 2004). The first component, assumed to represent pre-recruits and recruits, was identified in the length-frequency distribution for males obtained from known recruitment grounds in upper Spencer Gulf in February 2007 (mean 22.0 mm, SD 4.2 mm). The proportions at length l were assumed equal for male and female WKP and both stocks.
m	$m_l = a + \left\{ 1 \big/ \left[1 + \exp^{b(l - l_{50})} \right] \right\}$ $a = 8.3 \times 10^{-6}$, $b = -0.277$, $l_{50} = 36.45$	Logistic maturity (proportion) at length per female WKP; estimated from SG prawns (Carrick, 2003) and assumed for both stocks.
f	$f_l = a l^b$ $a = 0.794$, $b = 3.462$	Fecundity (egg production) at length per female WKP; estimated from GSV prawns (M. Kangas, unpublished; cited by Carrick, 2003) and assumed for both stocks.
w	$w_{l,s} = a_s l^{b_s} / 1000$ $a_{\text{male}} = 0.00124$, $b_{\text{male}} = 2.76$ $a_{\text{female}} = 0.00175$, $b_{\text{female}} = 2.66$	Average WKP weight (kg) at length l for sex s; estimated from SG prawns (Carrick, 2003) and assumed for both stocks.
M	M = 0.102	Instantaneous natural mortality month^{-1}; estimated from tag–recapture data on GSV prawns by conditional likelihood (Xiao and McShane, 2000a).
Estimated	n = 25 (GSVPF); n = 32 (SGPF)	The values and their variances and covariances were estimated.
ξ and Υ	$\alpha = E_0 (1 - h) \big/ (4hR_0)$ $\beta = (5h - 1) \big/ (4hR_0)$ $h = r_{\text{comp}} \big/ (4 + r_{\text{comp}})$ $r_{\text{comp}} = 1 + \exp(\xi)$ $R_0 = \exp(\Upsilon) \times 10^8$	Two parameters for the Beverton-Holt spawner-recruitment equation 2 (Table 4.7) that defined α and β (Haddon, 2001): 1) virgin recruitment (R_0) was estimated on the log scale; and 2) steepness (h) reparameterised based on recruitment compensation ratio r_{comp} (Goodyear, 1977). E_0 was the calculated overall equilibrium virgin egg production assuming no fishing mortality.

Model parameters	Equations, values and errors	Notes
μ_1 and κ	μ_1 and κ	Two parameters to describe the monthly (time-months 1…12) recruitment pattern (primary mode μ_1, and concentration κ), equation 4 (Table 4.7), according to a von Mises directional distribution (Mardia and Jupp, 2009). Proportion overlap of the mixture distribution τ was fixed ≅ 1, therefore secondary mode (μ_2) was not applicable.
l^{50} and δ	l_{f}^{50} and δ_{f}	Two (GSVPF) or four (SGPF) parameters for the estimated logistic vulnerability of prawns for fishing (f = fishery) or survey (s = survey), equation 7 (Table 4.7). δ governed the initial steepness of the curve and l^{50} was the length at 50% selection. For the GSVPF, fishery vulnerability parameter values were estimated to be the same as those from surveys.
$q^f(t)$	$q^{\mathrm{f}}(t)=\exp\left\{\log\left(\bar{q}^{\mathrm{f}}\right)-\varsigma\left[\cos(t)+\vartheta\sin(t)\right]\right\}$, where $t = 2\pi$seqmonth/12.	Fishery catchability was based on a sinusoidal function to model monthly patterns using the variable 'seqmonth'. As the maximum water temperature was in February, seqmonth = 1 in March and 12 in February. Two catchability parameters, amplitude (ς) and peak (ϑ), were estimated for the SGPF, whereas these were held constant (=0) for the GSVPF. The geometric mean catchabilities (f = fishery or f = survey) were calculated as closed-form mean estimates of standardised catch rates (fishery and survey) divided by the mid-month biomass (form 2 for fishery catchability; form 1 for survey catchability) (Table 4.7) (Haddon, 2001).

ζ	$\eta = \zeta$e
	e = zeros(nparRresid, nparRresid+1);
	for i = 1:nparRresid
	hh = sqrt(0.5 * i ./ (i + 1));
	e(i, 1:i) = -hh ./ i; e(i, i + 1) = hh;
	end; e = e ./ hh;
		Recruitment parameters to ensure log deviations sum to zero with standard deviation σ, equation 16 (Table 4.10). ζ were the 19 (GSVPF) or 22 (SGPF) estimated parameters known as barycentric or simplex coordinates, distributed *NID*(0,σ) with number nparRresid = number of recruitment years – 1 (Möbius, 1827; Sklyarenko, 2011). e was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill *et al.*, 2014).

(continued)

Model parameters were estimated by calibrating the model to standardised catch rates and size-composition data (Table 4.9). Primary importance was placed on fitting the standardised catch rates (Francis, 2011; Francis and Hilborn, 2011). Effective sample sizes for scaling multinomial likelihoods were calculated within the model to give realistic weighting to the size composition data. The effective sample size is defined as being roughly equivalent to the size of a hypothetical sample of independent and identically distributed (i.i.d.) prawns drawn from the entire population that would have the same amount of observation error as the observed sample (Pennington and Vølstad, 1994).

Table 4.9. Negative log-likelihood (NLL) functions for calibrating population dynamics.

NLL functions for:	Theory description	Equations
Log standardised catch rates c^f (NLL1) and c^s (NLL2):		
$\frac{n}{2}\left[\log(2\pi)+2\log(\hat{\sigma})+1\right]$, or simplified as $n\log(\hat{\sigma})$, where $\hat{\sigma}=\sqrt{\sum\left\{\left[\log(c)-\log(\hat{c})\right]^2\right\}/n}$ and n was the number of monthly catch rates.	Normal distribution (Haddon, 2001)	(9)
Length *l* (NLL3, males; NLL4, females) and grading *g* (NLL5) size-composition data:		
$-\sum\frac{1}{2}(\tilde{n}-1)(\log\nu-\nu/\hat{\nu})$, where $\tilde{n}$ was the total number of size categories (l or g) with proportion-frequency > 0, $\hat{\nu}=\frac{(\tilde{n}-1)}{2\sum\hat{p}\log(\hat{p}/p)}$, $\nu=\max(2,\hat{\nu})$ specified sample size bounds, $\hat{p}$ were the observed proportions > 0 and p were predicted.	Effective sample size (ν) in multinomial likelihoods (O'Neill *et al.*, 2011)	(10)
Ensuring exploitation rates range between 0 and 1 (NLL9):		
$0.5\sum\left\{\infty\left[\frac{\log(C_t/1000)-\log(B_t/1000)}{\sigma}\right]^2 b\right\}$, where σ was the user defined SD for penalty weighting (0.0005) and b was a logical switch for $C_t > B_t$.		(11)
Preventing unrealistically large population estimates and low estimates of harvest rate (NLL10):		
$0.5\left\{\left[\tilde{u}-\max\left(CN_y/R_y\right)\right]/\sigma\right\}^2 b$, where $\tilde{u}$ was the minimum annual harvest fraction 0.1, σ was the user defined SD for penalty weighting (0.005), CN_y was the annual total number of WKP caught, R_y the annual recruitment, and b was a logical switch for $\max\left(CN_y/R_y\right)<\tilde{u}$.	Optimisation penalty (Hall and Watson, 2000)	(12)
Log survey exploitable biomass estimates (NLL13):		
Same function type as NLL1,2, *substituting predicted and observed biomass estimates, and number of observed biomass estimates*		(13)

Due to the relatively uninformative (flat) annual trend in WKP catch rates from the SGPF, penalty terms were used to ensure exploitation rates ranged between zero and one, and avoid the optimisation converging to unrealistically large population sizes with low improbable estimates of harvest rate (Table 6.9; O'Neill and Turnbull, 2006; O'Neill *et al.*, 2014). Further penalty terms were used to ensure the length at which prawns were vulnerable to the gear during surveys ($l^{50}_{\mathrm{f=survey}}$) were within reasonable bounds and less than vulnerability during fishing ($l^{50}_{\mathrm{f=fishery}}$) (Table 4.10). Negative log-likelihood (NLL) functions for prior distributions were also prepared for recruitment compensation ratio (r_{comp}), instantaneous natural mortality (M) and annual recruitment variation (η) (Table 4.10), although the function for mortality was not required since M was assumed to be fixed at 0.102 month^{-1} (Xiao and McShane, 2000a).

Table 4.10. Negative log-likelihood (NLL) functions for parameter bounds and distributions.

NLL functions for:	Equations
Recruitment compensation ratio r_{comp} (NLL6):	
$0.5\{[\xi - \log(4-1)]/\sigma\}^2 \times [\xi > \log(19)]$, where σ = 0.005 defined the negative log-likelihood.	(14)
Instantaneous natural mortality M month^{-1} (NLL7):	
$0.5[(M - 0.102)/\sigma]^2$, where σ = 0.031 defined the prior distribution.	(15)
Annual log recruitment deviates η_y (NLL8):	
$\frac{n}{2}\left[\log(2\pi) + 2\log(\sigma) + (\hat{\sigma}/\sigma)^2\right]$, where $\sigma = \min\{\max(\hat{\sigma}, \sigma_{\min}), \sigma_{\max}\}$, $\sigma_{\min} = 0.1$ and $\sigma_{\max} = 0.4$ specified bounds, $\hat{\sigma} = \sqrt{\sum \eta_y^2 / n}$, and n was the number of recruitment years y.	(16)
Penalty/prior for l_s^{50} (NLL11):	
$0.5\left[\left(l_s^{50} - 30\right)/\sigma\right]^2 b$, where σ was the user defined SD for penalty weighting (0.005) and b was a logical switch for $l_s^{50} < 20$ or $l_s^{50} > 40$. NLL11 was not influential.	(17)
Penalty/prior for $l_f^{50} < l_s^{50}$ (NLL12):	
$0.5\left[\left(l_s^{50} - l_f^{50}\right)/\sigma\right]^2 b$, where σ was the user defined SD for penalty weighting (0.005) and b was a logical switch for $l_f^{50} < l_s^{50}$. NLL12 was not influential.	(18)

The log-likelihood function for survey exploitable biomass required observed estimates. These were determined by: 1) calculating the fishable area (≥10 m depth; Figure 4.1) for each region using ArcGIS® software; 2) extrapolating mean survey catch rate (per trawled area) to the fishable area for each region; 3) summing across the whole gulf; then 4) dividing by a retention factor of 0.5 (i.e. the fraction of WKP in the swept area assumed to be retained in the codend; Joll and Penn, 1990).

The estimation process consisted of a maximum likelihood step using Matlab's 'fminsearch' optimiser routine, followed by a simulated annealing variant (Kirkpatrick *et al.*, 1983) of Markov Chain Monte Carlo sampling (MCMC) to search further maximum likelihood solutions and estimate the parameter covariance matrix. Simulated annealing is an efficient method for locating a good approximation of the global minimum among many local minima. We used this technique to simultaneously determine solutions for the estimated parameters over the log-likelihood space. Simulated annealing was started from a NLL scaling factor of 100, then reduced to 10 and 1, with a minimum of 5000 iterations (jumps) conducted at each level. The covariance matrix is built up from the differences in the log-likelihood space with each jump.

During the fitting process different model solutions were estimated from the size composition data versus the standardised catch rates. To address this problem, the maximum likelihood estimation process was conducted in two stages: firstly, to estimate selectivity and recruitment pattern parameters; and secondly, to fix these parameters in a second optimisation tuned primarily to catch rate data (Francis, 2011; Francis and Hilborn, 2011) (Table 4.11; Table 4.12). This two stage approach was undesirable and further work is required to achieve simultaneous model fits to both the size composition and standardised catch rate data. Given that simultaneous model fits could not be achieved, we did not proceed with the MCMC step (Figure 4.5), which was programmed to document further parameter solutions around the maximum likelihood results from simulated annealing; the MCMC model fitting adds further computation time to the overall process.

Table 4.11. The two-stage approach used to estimate parameters for the GSVPF model (0 = fixed, assumed value in parentheses; 1 = estimated). Abbreviations: S1, Stage 1; S2, Stage 2; n/a, not applicable; NLL, negative log-likelihood.

Parameter	Stage 1	Stage 2
ξ	1	1
Υ	1	1
μ_1	1	0 (=S1)
μ_2	0 (n/a*)	0 (n/a*)
κ	1	0 (=S1)
π	0 (≈1)	0 (≈1)
l_s^{50}	1	0 (=S1)
δ_s	1	0 (=S1)
l_f^{50}	0 (n/a)	0 (= l_s^{50}, S1)
δ_f	0 (n/a)	0 (= δ_s, S1)
M	0 (=0.102)	0 (=0.102)
ς	0 (=0)	0 (=0)
ϑ	0 (=0)	0 (=0)
η_y	1	1
NLL switch		
On	NLL1-6,8,9,11,13	NLL1,2,5,6,8,9,13
Off	NLL7,10,12	NLL3,4,7,10-12

*μ_2 is n/a when π ≈ 1 (i.e. complete overlap, no second recruitment distribution/mode estimated).

Table 4.12. The two-stage approach used to estimate parameters for the SGPF model (0 = fixed, assumed value in parentheses; 1 = estimated). Abbreviations: S1, Stage 1; S2, Stage 2; n/a, not applicable; NLL, negative log-likelihood.

Parameter	Stage 1	Stage 2
ξ	1	1
Υ	1	1
μ_1	1	0 (=S1)
μ_2	0 (n/a*)	0 (n/a*)
κ	1	0 (=S1)
π	0 (≈1)	0 (≈1)
l_s^{50}	1	0 (=S1)
δ_s	1	0 (=S1)
l_f^{50}	1	0 (=S1)
δ_f	1	0 (=S1)
M	0 (=0.102)	0 (=0.102)
ς	1	1
ϑ	1	1
η_y	1	1
NLL switch		
On	NLL1-6,8,9,11-13	NLL1,2,6,8,9,13
Off	NLL7,10	NLL3-5,7,10-12

*μ_2 is n/a when π ≈ 1 (i.e. complete overlap, no second recruitment distribution/mode estimated).

4.2.3 Economic (model and) parameters

The economic model calculated net present value (NPV) based on total discounted profit theory (Ross, 1995). The NPV objective function used geometric discounting that summed profits over future model projections:

$$\mathrm{NPV} = \sum_{y=1}^{\infty} a^{y} \pi_{y},$$

where $a = (1 + i)^{-1}$, i was the annual interest (discount) rate and π_y was the profit during year y. To avoid model projections over many years, the NPV was truncated to a terminal year T and equilibrium was assumed thereafter:

$$\mathrm{NPV} = \sum_{y=1}^{T-1} a^{y} \pi_{y} + a^{T-1} i^{-1} \pi_{T}.$$

This NPV function differs from Equation (13) of Punt *et al.* (2010), in that we consistently discounted annual profits back to the start of the first projection.

Annual profit was calculated as the harvest value minus the variable and fixed costs:

$$\pi_{y} = \sum_{t} \left(\sum_{l} v_{t,l} C_{t,l} - \Omega_{t}^{\mathrm{V}} \right) + \overline{B}^{by} \left(1 - c_{L}\right) E_{y} - \left(\Omega_{y}^{\mathrm{F}} V_{y} \right),$$

where $v_{t,l}$ was the average price received by fishers for WKP by time-month t and length class l (Figure 4.4), $C_{t,l}$ was the WKP harvest weight, Ω_{t}^{V} was the total variable costs, $\overline{B}^{by}$ was the average by-product value ($) taken each boat day, c_L was the share of the catch paid to crew members (a labour cost), E_y was the total annual boat days fished, Ω_{y}^{F} the average annual fixed costs, and V_y was the number of vessels (Table 4.5; Table 4.6).

Variable costs Ω_{t}^{V} were calculated by time-month t. This included the proportional labour cost (c_L), cost of packaging and marketing (c_M) per unit weight of catch, cost of repairs and maintenance per boat-day (c_K), fuel cost per boat-day (c_F), and other incidental costs per boat-day (c_O) (Table 4.5; Table 4.6):

$$\Omega_{t}^{\mathrm{V}} = \sum_{l} \left(c_{L} v_{t,l} + c_{M} \right) C_{t,l} + \left(c_{K} + c_{F} + c_{O} \right) E_{t}.$$

Average annual fixed costs Ω_{y}^{F} were calculated using annual vessel costs (W_y), and opportunity (o) and depreciation (d) rates on average total investment value per vessel (K_y) (Table 4.5; Table 4.6):

$$\Omega_{y}^{\mathrm{F}} = \left[W_{y} + (o + d) K_{y} \right].$$

Annual vessel costs (W_y) were not related to fishing effort. They were the sum of costs needed to support a vessel before fishing.

4.3 Simulation and management procedures

Model simulations were used to estimate management reference points and evaluate proposed management procedures (MPs). Ten-year projections, from 2014 to 2023, were simulated using full model error methodology similar to Richards *et al.* (1998). As base reference to these projections, 1000 random variations of the estimated parameters (GSVPF: n = 25; SGPF: n = 32) were created from the simulated annealing covariance matrix. For economics, 1000 random variations on parameters listed in Table 4.5 and Table 4.6 were generated based on an estimated CV of 10% for variable and fixed costs and calculated CV of 15% for by-product revenue. These variations of parameter estimates were used to simulate future uncertainties, including stochastic recruitment.

Equilibrium reference points for MSY and MEY_v for each fishing power level were calculated by optimising the population and economic models through mean monthly fishing mortality proportional to fishing effort. All parameter uncertainties as outlined above were included except stochastic recruitment variation. The population dynamics were propagated to equilibrium using the monthly fishing pattern calculated from data for the last five fishing years (2009—2013).

Ten MPs for the GSVPF and 14 MPs for the SGPF were developed by consultation with fishery managers and stakeholders through face-to-face meetings and teleconferences (Table 4.13; Table 4.14). The first MP for each fishery was status quo. For the GSVPF, status quo is 10 vessels operating for a total of 260 vessel-nights (eight-year mean: 2005—2012) in November, December and March—June (6 months), and with a pre-Christmas catch cap for the fleet of 40 t. For the SGPF, status quo is 39 vessels operating for a total of 2000 vessel-nights (nine-year mean: 2005—2013) in November, December and March—June (6 months), and with a variable pre-Christmas catch cap (dependent on the November stock assessment survey). Relative to status quo (MP1), the remaining MPs for each fishery were characterised by one or a combination of: i) reductions in the number of vessels; ii) increases in total effort; iii) changes in the pre-Christmas catch cap; iv) temporal closures; v) spatial closures; and vi) introduction of an annual quota. Where a MP included a reduction in the number of vessels, a notional increase in fishing power (and associated costs) for the remaining vessels was included in the simulation, as it was assumed that smaller or least powerful vessels would exit the fishery first.

Since the operating model does not account for spatial structuring of the population, the effect of closed areas in MP8 for the GSVPF and MP10, MP11 and MP12 for the SGPF was mimicked by estimating the proportions of the stock inside and outside those areas during the relevant months. Using geographical information systems (GIS) techniques, these estimates were based on the product of average nominal catch rate by trawled area scaled up to the fishable area.

Each MP was simulated to evaluate management performance over ten years against twelve performance measures grouped into four categories: i) industry functioning: average annual harvest and effort; ii) current performance indicators (Dixon and Sloan, 2007; PIRSA, 2014): average catch rates (fishery and survey) and average prawn size (length and size grade); iii) 2023 population status: spawning egg production and exploitable biomass; and iv) economics: relative profit and NPV against variable costs only and both variable and fixed costs. The NPV calculated over all future years was used to record a long-term benefit for fishing WKP after 10 years, whereas the other performance measures were averaged over 10 years to provide a shorter-term perspective.

Simulated total fishing effort was split across months based on the logbook-derived average annual pattern of 2009-2013. The contribution of a month towards the annual pattern was normalised with a mean of 1. Negligible effort was recorded in October and February, so these months were omitted from calculation of the annual effort pattern (along with the other non-fishing months of January and July to September). If a month was closed to fishing, that month's fishing effort was reallocated to other months in proportion to the normalised pattern.

Table 4.13. Management procedures for the GSVPF developed by consultation and simulated over ten future years. Bullets (•) indicate same as status quo.

Management brief	Management procedures					
	Number of vessels	**TAC**	**Total effort (vessel-nights)**	**Pre-Christmas catch cap**	**Fishing months**	**Area closed**
1. *Status quo*	*10*	*None*	*260*	*40 t*	*Nov, Dec, Mar-Jun (6)*	*None*
2. Reduce number of vessels	7	•	•	•	•	•
3. Reduce number of vessels	5	•	•	•	•	•
4. Reduce number of vessels, increase total effort	7	•	300	•	•	•
5. Reduce number of vessels, increase total effort	7	•	350	•	•	•
6. Reduce number of vessels, increase total effort	7	•	400	•	•	•
7. Reduce number of vessels, increase pre-Christmas catch cap	7	•	•	60 t	•	•
8. Reduce number of vessels, alternate closure of upper (Zone A*) and lower gulf (Zone C†)	7	•	•	•	•	Zone C (Nov, Dec, Mar), Zone A (Apr-Jun)
9. Reduce number of vessels, set quota, no effort limit, fish all months	7	180 t	No limit	No cap	All months (12)	•
10. Reduce number of vessels, set quota, no effort limit, fish all months	7	250 t	No limit	No cap	All months (12)	•

* Zone C comprises Blocks 23-27, 38-45 and 53-121 of Region 3, Region 4, part of the 'Hole' and Investigator Strait.
† Zone A comprises Blocks 1-9, 14-18 and 31-33 of Region 1 and Region 6.

Table 4.14. Management procedures for the SGPF developed by consultation and simulated over ten future years. Bullets (•) indicate same as status quo.

Management brief	Management procedures					
	Number of vessels	TAC	Total effort (vessel-nights)	Pre-Christmas catch cap	Fishing months	Area closed
1. *Status quo*	*39*	*None*	*2000*	*Variable*	*Nov, Dec, Mar-Jun (6)*	*None*
2. Reduce number of vessels	33	•	•	•	•	•
3. Reduce number of vessels	30	•	•	•	•	•
4. Reduce number of vessels, no pre-Christmas catch cap, fish all months	20	•	•	No cap	All months (12)	•
5. Reduce number of vessels, no pre-Christmas catch cap, fish all months	12	•	•	No cap	All months (12)	•
6. Close fishery in November	•	•	•	•	Dec, Mar-Jun (5)	•
7. Reduce pre-Christmas catch cap	•	•	•	-40%	•	•
8. Close fishery in March	•	•	•	•	Nov, Dec, Apr-Jun (5)	•
9. Close fishery in June, increase pre-Christmas catch cap	•	•	•	+190 t	Nov, Dec, Mar-May (5)	•
10. Close northern gulf* in March	•	•	•	•	•	Northern gulf (Mar)
11. Close fishery in March and northern gulf in April	•	•	•	•	Nov, Dec, Apr-Jun (5)	Northern gulf (Apr)
12. Close 'North End'† of Gutter region in November and December	•	•	•	•	•	'North End' (Nov, Dec)
13. Set quota, no effort limit, fish all months	•	1950 t	No limit	•	All months (12)	•
14. Set quota, no effort limit, fish all months	•	2200 t	No limit	•	All months (12)	•

* Northern gulf comprises Blocks 1-44 and 109-125 of North, Middlebank, part of Wallaroo and part of Cowell regions.
† 'North End' comprises Blocks 51 and 52 of the 'Gutter' (part) region.

4.4 Summary of bio-economic model

In summarising its completeness and sophistication, the WKP bio-economic model incorporates the following features:

1. A full length-based fishery population dynamics model sits at the centre of it all;
2. Fishery and survey catch rates were standardised;
3. Size-transition matrices were estimated (using a method described in Appendix C);
4. Effective sample sizes were accounted for in the weighting of size composition (length and grade frequency) data;
5. Model parameters were either assumed (fixed) or estimated using a maximum likelihood method;
6. A parameter covariance matrix was obtained by simulated annealing;
7. Inclusion of vessel-based fishery economics;
8. A projection model was constructed to simulate MPs over ten future years of stochastic recruitment;
9. The specific MPs were obtained from consultation with industry and managers;
10. Variation and parameter uncertainty (from the covariance matrix) are explicit in the simulations; and
11. Performance of each MP was evaluated holistically using a suite of biological, industry and economic measures.

5 Results

5.1 Model calibration and description

The length-based model was calibrated to capture the population dynamics of the WKP populations in the GSV and SG as accurately as possible with the available data and biological information.

5.1.1 Gulf St Vincent Prawn Fishery

The model tracked the standardised fishery and survey catch rate annual trends, although not some of the seasonal peaks and troughs, particularly for fishery catch rates in the last several years (Figure 5.1; Figure 5.2). As expected, increased catch rates were predicted when the fishery was closed (1991, 1992 and 2013). Standard deviations of the standardised residuals were 1.00 and 1.02 for fishery and survey catch rates, respectively. Francis and Hilborn (2011) report that a good model fit is conditional on a standard deviation of normalised (or standardised) residuals (SDNR) not much greater than 1, along with a check of the plot of observed and predicted abundance data (catch rates).

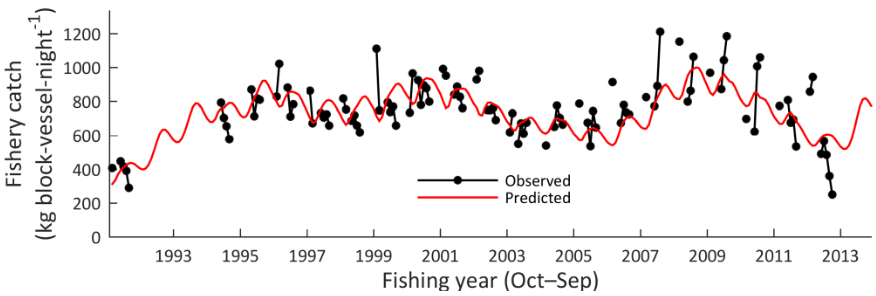

Figure 5.1. Observed (standardised) and predicted fishery catch rates for the GSVPF from 1991—2013.

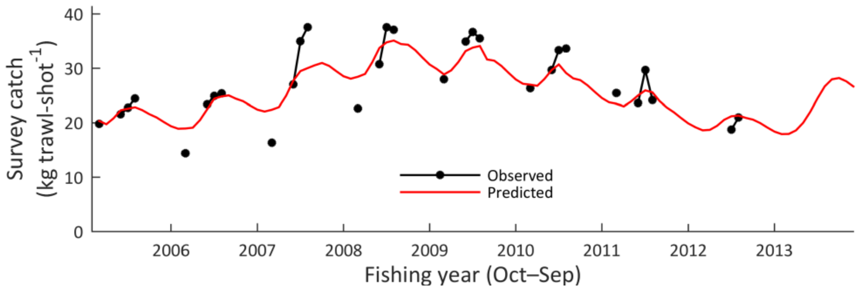

Figure 5.2. Observed (standardised) and predicted survey catch rates for the SGPF from 2005—2013.

Since the adoption of a consistent survey design in the GSVPF in 2005, fishing catch rates have correlated reasonably well with survey catch rates, except in December (Figure 5.3). Of all the survey months (December, March, April and May), December is considered the least representative of stock size as the peak spawning activity of WKP around this time is likely to affect their catchability, thus impacting on catch rates from the fixed survey locations (Figure F.12). In contrast, fishery catch rates in December are often elevated (Figure F.10) as a result of harvest decision criteria allowing the fleet to target smaller prawns, thus affording a greater level of protection for large spawners while also taking advantage of the high Christmas prices paid for small prawns (Dixon and Sloan, 2007).

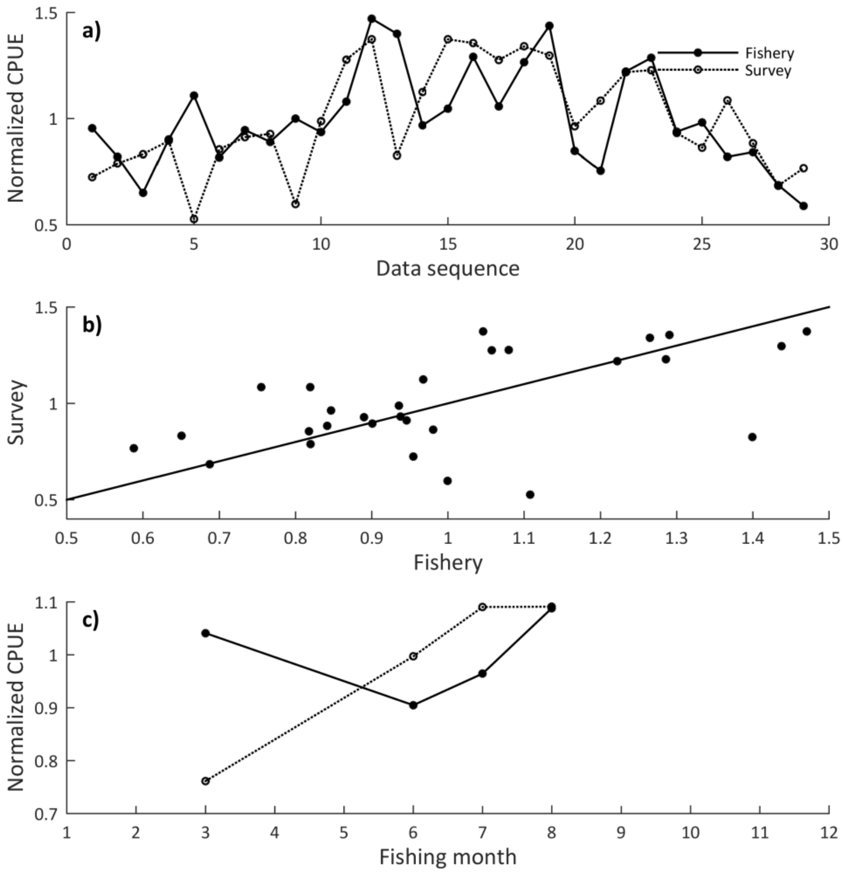

Figure 5.3. Comparison of standardised fishery and survey catch rate (CPUE) trends in the GSVPF by: a) data sequence; b) regression; and c) fishing month. Note: catch rates were normalised to ensure trends were on the same scale.

The large effective sample sizes for male and female length-frequency distributions (>100 for most survey months) obtained from surveys and high agreement between observed and predicted length-class assignments (Figure 5.4; Figure 5.5) implied good representation of the population size structure (O'Neill *et al.*, 2011). Weighting the length-frequency data (via its multinomial log-likelihood) with the effective sample size rather than the actual sample size helped to account for any bias caused by schooling behaviour of WKP, whereby prawns of the same or similar age/length may school together and therefore appear as clusters in samples.

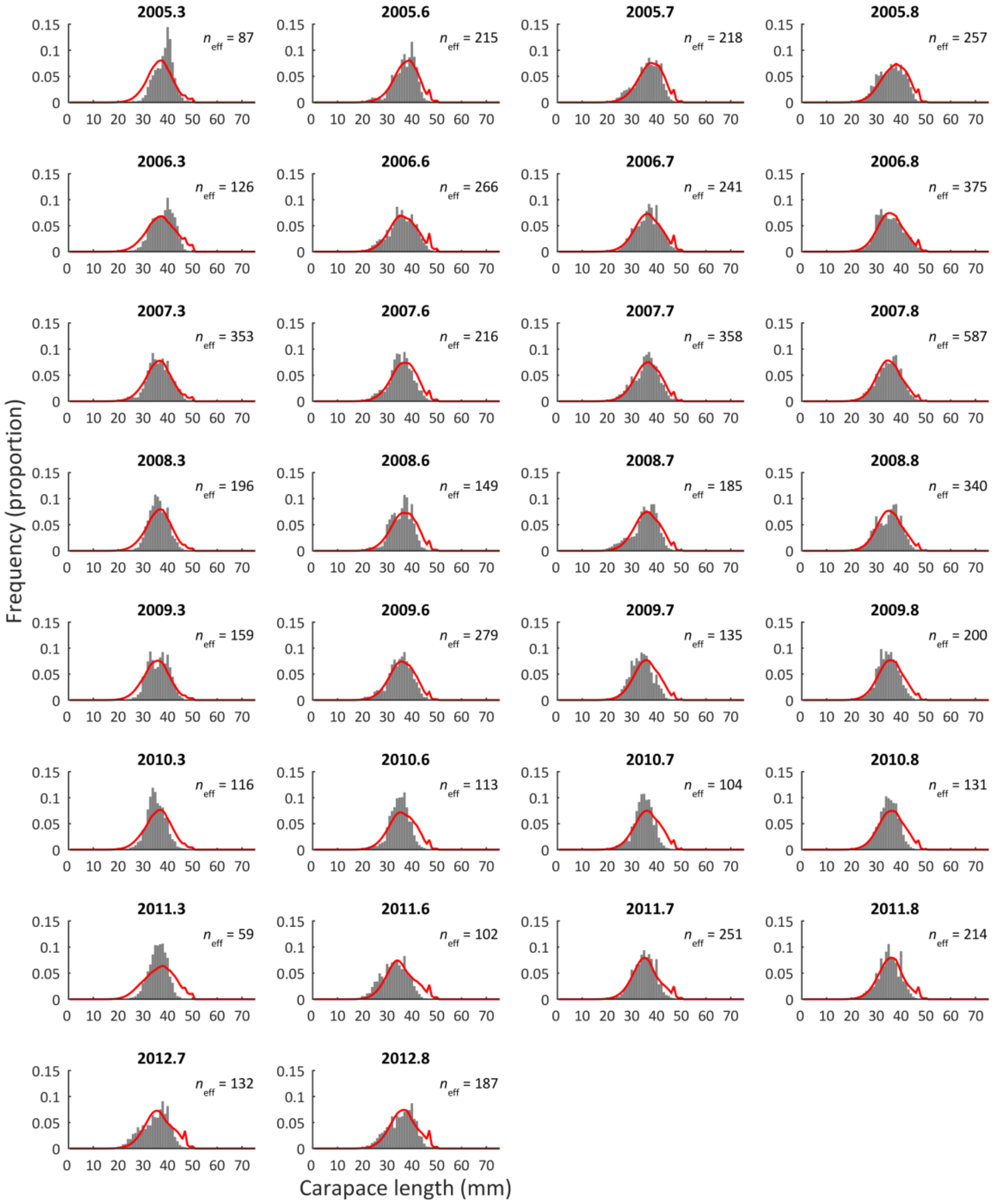

Figure 5.4. Observed (bars) and predicted (red line) survey length-frequency distributions (proportions) for male WKP in the GSVPF from 2005—2012. Labels refer to fishing year and month; n_{eff} indicates the effective multinomial sample size for each survey.

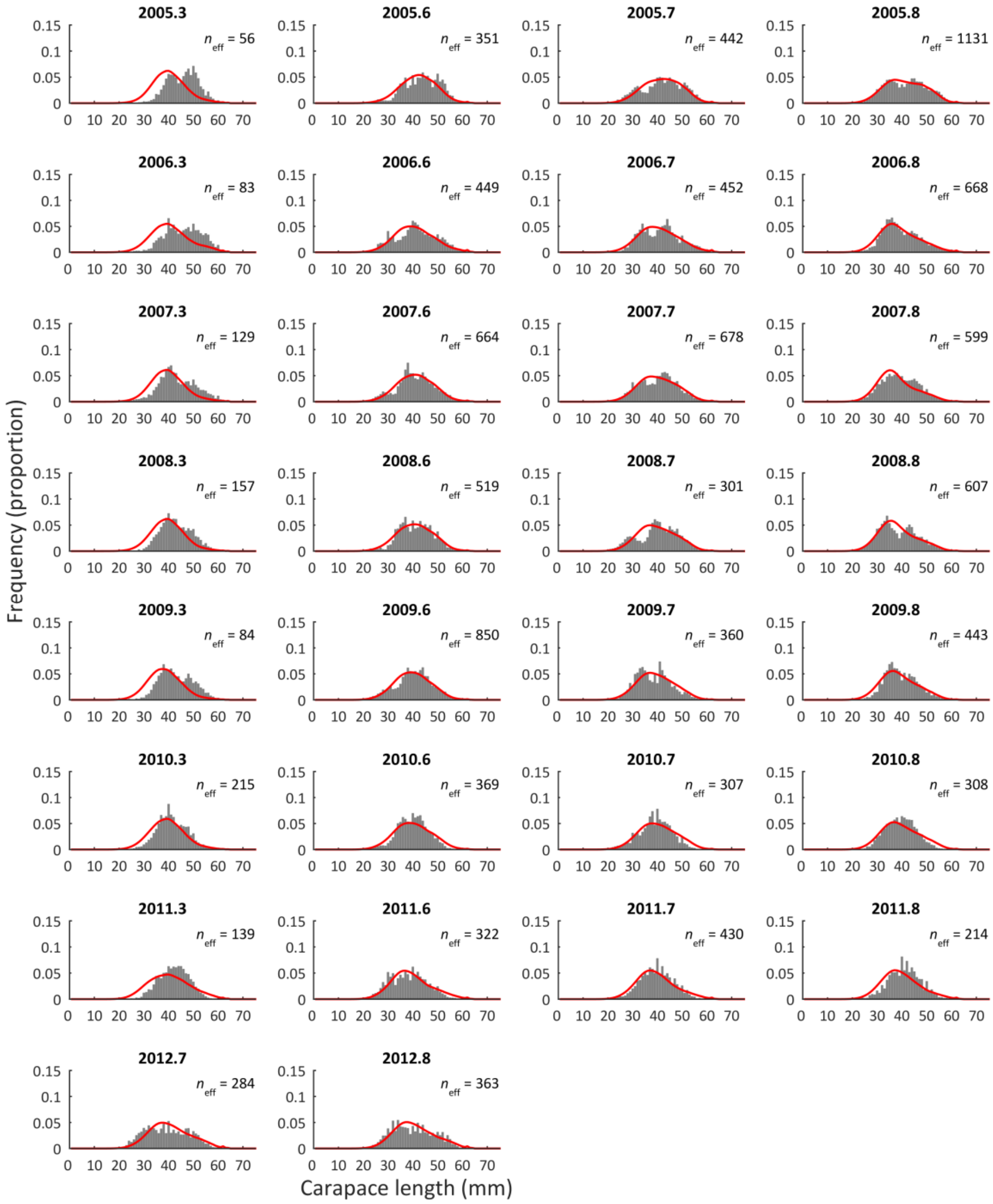

Figure 5.5. Observed (bars) and predicted (red line) survey length-frequency distributions (proportions) for female WKP in the GSVPF from 2005—2012. Labels refer to fishing year and month; n_{eff} indicates the effective multinomial sample size for each survey.

The model predicted that historical WKP spawning egg production and exploitable biomass in the GSVPF, expressed as a median ratio relative to the start of the 1969 fishing year, had fallen to <10% in 1984, with recruitment declining to ~36% of its virgin state the following year (Figure 5.6; Appendix Figure F.8). The stock status measures increased following the two-year closure of 1991—1992. Thereafter, egg production and biomass ratios varied roughly between 60% and 90%, and recruitment between 60% and 130% of 1969 levels. Despite egg production and exploitable biomass ratios falling to such precarious levels in 1984 (<10%) and remaining <20% until 1988, recruitment was predicted to drop below 40% only once in the fishery's history (1985) (Appendix Figure F.8).

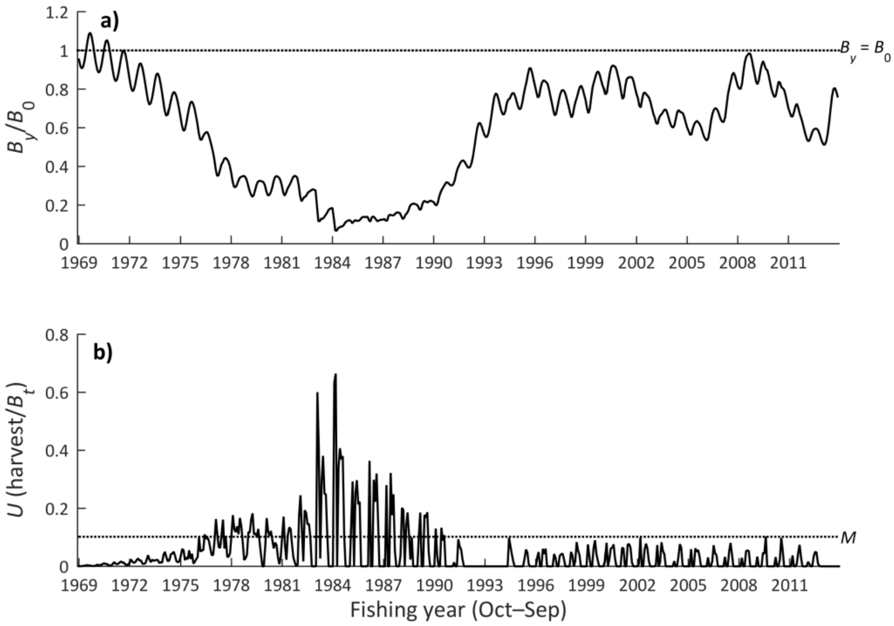

Figure 5.6. a) Monthly WKP exploitable biomass ratio (B_y/B_0) and b) harvest fraction in the GSVPF from 1969—2012. The dotted reference lines in plots a) and b) indicate the estimated level of the virgin stock (i.e. t = 0 at 1969) and the assumed natural mortality, respectively.

Virgin recruitment (R_0) was estimated at 5.74 × 10^7 for the GSVPF (Figure 5.7; Table 5.1). The related steepness parameter (h) of the stock recruitment relationship was calibrated at 0.60, indicating that 60% of pre-fishery recruitment (R_0) could be expected at 20% of virgin spawning stock. The recruitment mode (μ_1) was estimated in April. The mean carapace length at which 50% of the WKP population is vulnerable to the gear during fishing (l_f^{50}; derived from the survey parameter l_s^{50}) was 33.3 mm. There were no concerning correlations among the key estimated parameters (Table 5.2). Catchability was kept constant throughout the year since earlier model fits yielded unrealistic results when seasonal catchability parameters were estimated. Instantaneous natural mortality (M) was also fixed at 0.102 month^{-1}, estimated by Xiao and McShane (2000a).

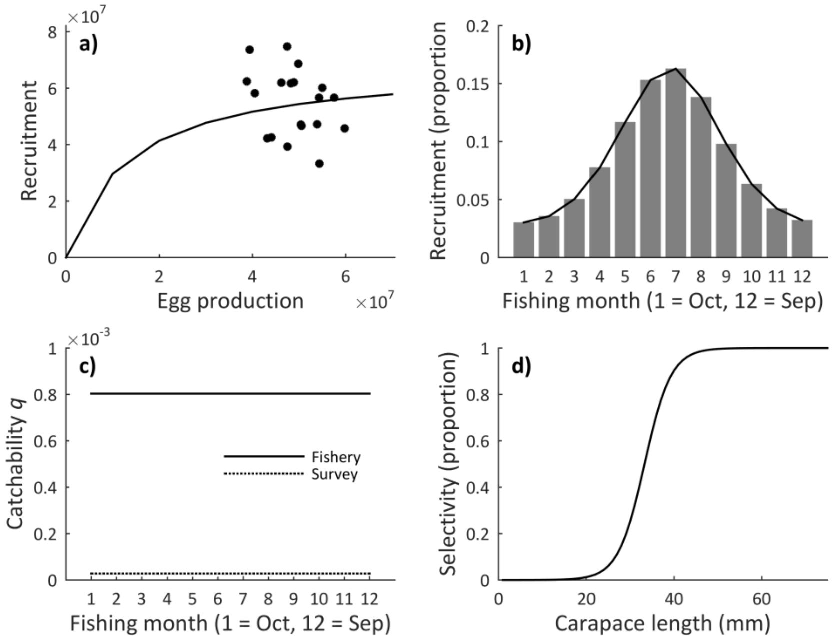

Figure 5.7. Predicted relationships for WKP in the GSVPF: a) stock-recruitment relationship (based on 19 years of modelled stochastic recruitment, 1994—2012); b) recruitment pattern (proportion); c) fishery and survey catchability; and d) vulnerability at carapace length (from surveys). Note: fishery and survey catchability were held constant throughout the fishing year.

Table 5.1. Parameter estimates and standard errors for GSVPF model calibration (NLL: Stage 1, -5048.2; Stage 2, -48.2). η_4 corresponds to the first year for estimating recruitment residuals (1994).

Parameter	Estimate	Standard error	Estimate transformed
ξ	1.629	0.076	0.604
Υ	-0.554	0.035	0.574
μ_1	6.770	0.143	
κ	0.848	0.090	
l_s^{50}	33.252	0.188	
δ_s	0.331	0.022	
l_f^{50}	-	-	
δ_f	-	-	
ς	-	-	
ϑ	-	-	
η_1	-	-	
η_2	-	-	
η_3	-	-	
η_4	-0.014	0.141	
η_5	-0.240	0.128	
η_6	-0.017	0.126	
η_7	0.085	0.147	
η_8	0.240	0.113	
η_9	0.118	0.130	
η_{10}	-0.038	0.147	
η_{11}	-0.251	0.130	
η_{12}	-0.215	0.122	
η_{13}	-0.262	0.122	
η_{14}	-0.241	0.097	
η_{15}	0.094	0.080	
η_{16}	0.313	0.089	
η_{17}	0.093	0.092	
η_{18}	-0.040	0.098	
η_{19}	-0.247	0.123	
η_{20}	-0.516	0.104	
η_{21}	-0.304	0.123	
η_{22}	0.196	0.157	

Table 5.2. Correlation matrix of the six leading model parameters estimated for the GSVPF. Correlation strength increases with cell-shading intensity.

	ξ	Υ	μ_1	κ	l_s^{50}	δ_s
ξ	1.00					
Υ	-0.60	1.00				
μ_1	0.07	0.02	1.00			
κ	0.02	0.11	0.07	1.00		
l_s^{50}	-0.18	-0.02	-0.34	-0.09	1.00	
δ_s	0.02	0.06	0.05	0.27	-0.31	1.00

5.1.2 Spencer Gulf Prawn Fishery

Diagnostic plots of standardised residuals indicated that the SGPF model fitted the data appropriately and the assumed error structures were valid (Appendix Sections G.3 and G.4). The model tracked the standardised fishery and survey catch rate annual trends reasonably well (Figure 5.8; Figure 5.9). Standardised fishery catch rates fluctuated seasonally and were generally stable; however, the time series comprised two distinct periods where the mean underwent an increase from ~590 kg block-vessel-night^{-1} for 1991—1997 to ~920 kg block-vessel-night^{-1} for 1998—2013. The model detected this shift quite well. The SDNR was 0.97 for fishery catch rates and 1.02 for survey catch rates.

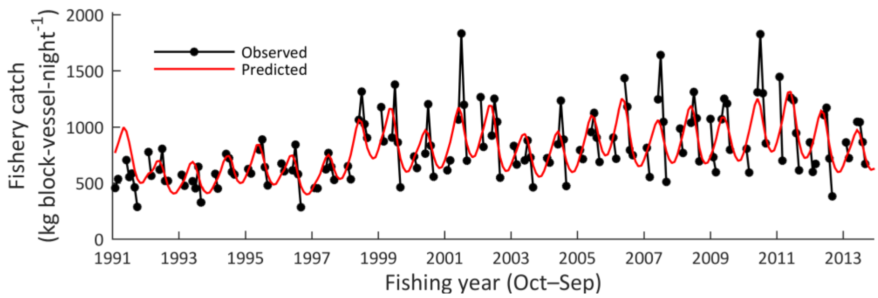

Figure 5.8. Observed (standardised) and predicted fishery catch rates for the SGPF from 1991—2013.

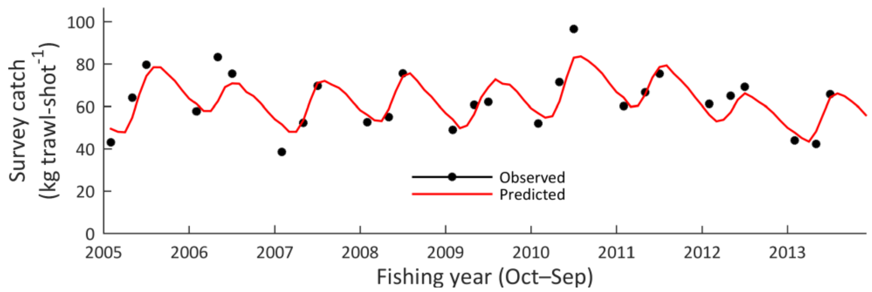

Figure 5.9. Observed (standardised) and predicted survey catch rates for the SGPF from 2005—2013.

Fishing and survey catch rates in the SGPF have correlated very well since a consistent survey design was adopted in 2005 (Figure 5.10). Normalised mean catch rates for each survey month (November, February and April) were almost identical.

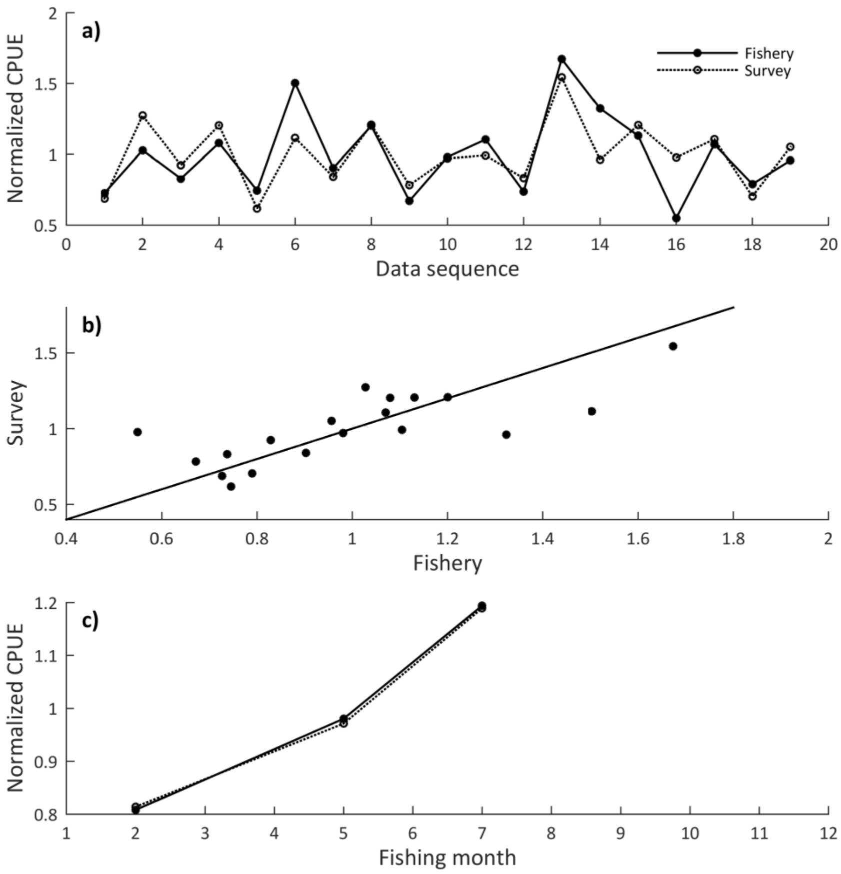

Figure 5.10. Comparison of standardised fishery and survey catch rate (CPUE) trends in the SGPF by: a) data sequence; b) regression; and c) fishing month. Note: catch rates were normalised to ensure trends were on the same scale.

The large effective sample sizes for male and female length-frequency distributions (>100 for most survey months) obtained from surveys and high agreement between observed and predicted length-class assignments (Figure 5.11; Figure 5.12) implied very good representation of the population size structure (O'Neill *et al.*, 2011). Large effective sample sizes were also estimated for approximately half of the commercial size-grade distributions (Figure 5.13). The smaller estimated sample sizes for some samples were typical of fisheries data (Pennington and Vølstad, 1994), and indicated that prawns within those samples were correlated, not necessarily that the model didn't fit the data.

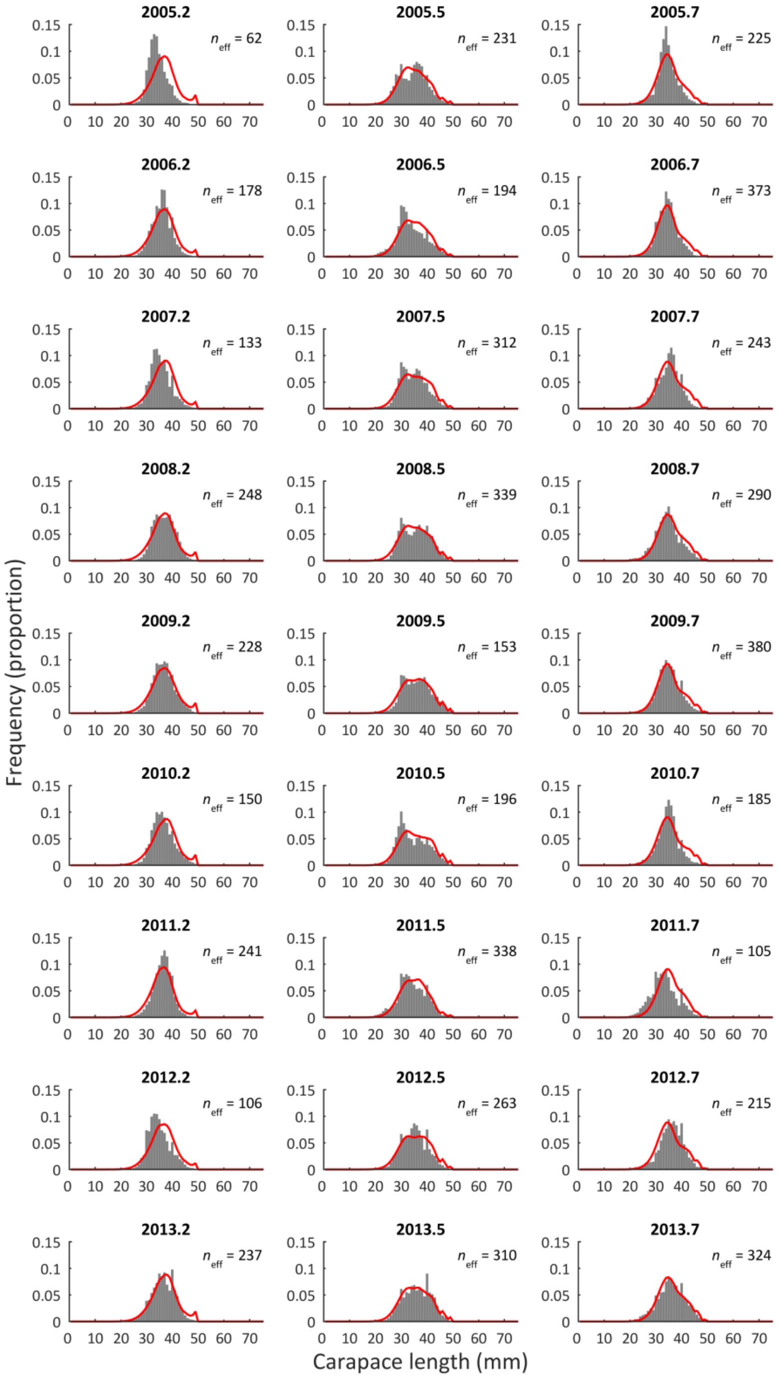

Figure 5.11. Observed (bars) and predicted (red line) survey length-frequency distributions (proportions) for male WKP in the SGPF from 2005—2013. Labels refer to fishing year and month; n_{eff} indicates the effective multinomial sample size for each survey.

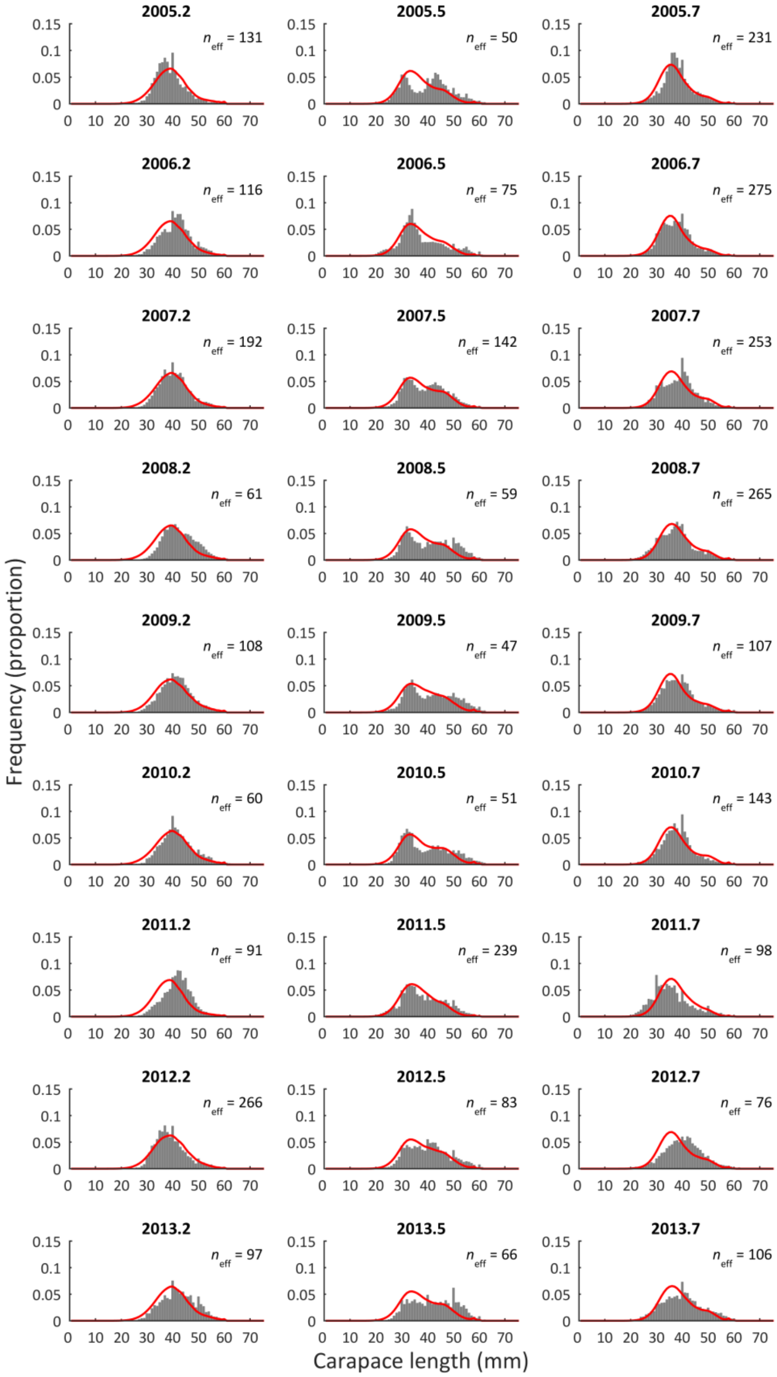

Figure 5.12. Observed (bars) and predicted (red line) survey length-frequency distributions (proportions) for female WKP in the SGPF from 2005—2013. Labels refer to fishing year and month; n_{eff} indicates the effective multinomial sample size for each survey.

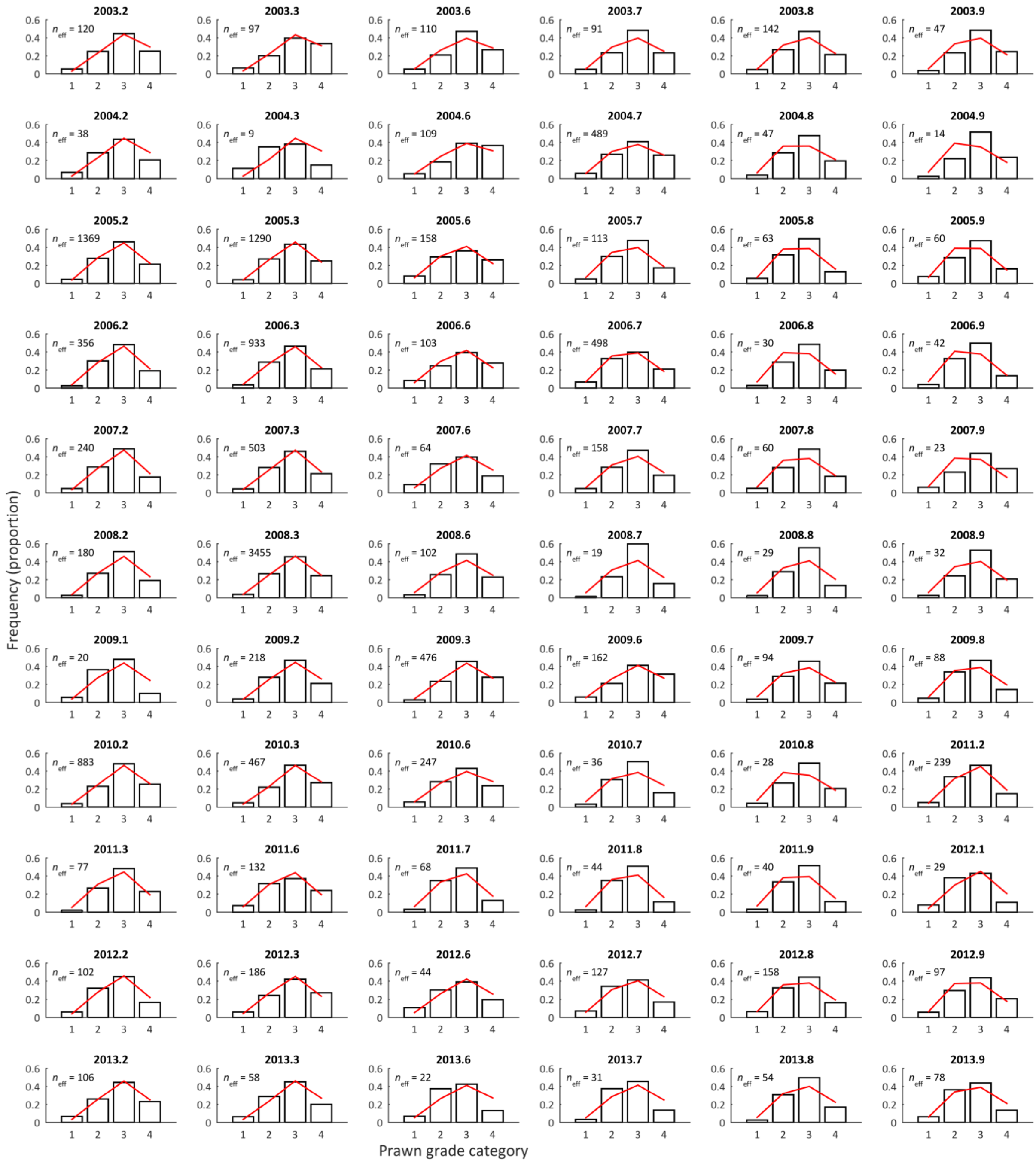

Figure 5.13. Observed (bars) and predicted (red line) size-grade frequency distributions (proportions) in the SGPF from 2003—2013. Size-grade categories: 1 = >20 lb^{-1}; 2 = 16-20 lb^{-1}; 3 = 10-15 lb^{-1}; 4 = <10 lb^{-1}. Labels refer to fishing year and month, and n_{eff} indicates the effective multinomial sample size for each month.

The length-based model for the SGPF predicted that historical WKP spawning egg production and exploitable biomass, expressed as a median ratio relative to the start of the 1969 fishing year, had declined to 40-45% in 1993 (Figure 5.14; Appendix Figure G.8). Thereafter, egg production and biomass ratios trended upwards to 80-85% in 2010—2011 before declining to 62-67% in 2013. Relatively large fluctuations in recruitment have occurred since the 1990 fishing year, ranging between 65% and 142% of its virgin state (Appendix Figure G.8).

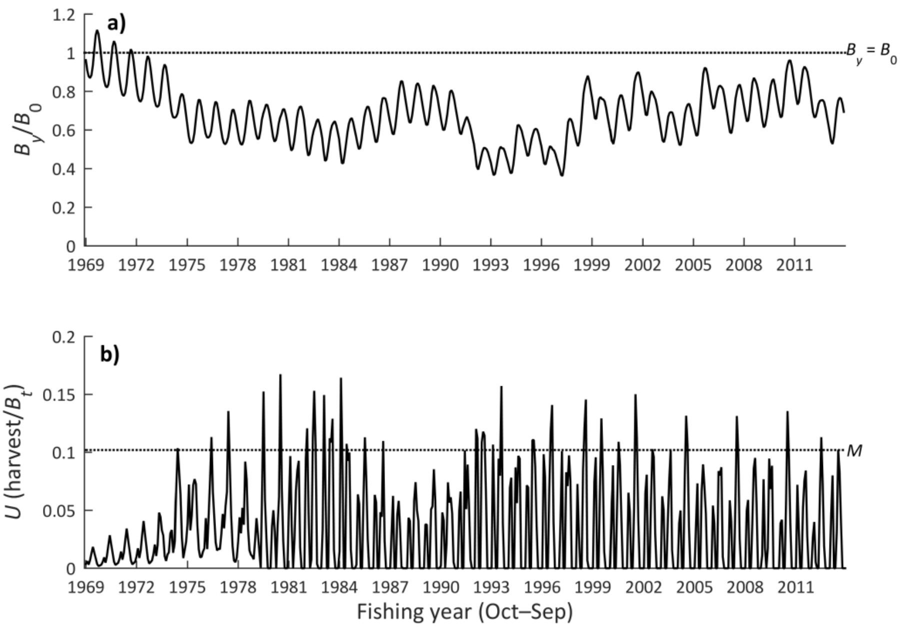

Figure 5.14. a) Monthly WKP exploitable biomass ratio (B_y/B_0) and b) harvest fraction in the SGPF from 1969—2013. The dotted reference lines in plots a) and b) indicate the estimated level of the virgin stock (i.e. t = 0 at 1969) and the assumed natural mortality, respectively.

Virgin recruitment (R_0) was estimated at 2.99 × 10^8 for the SGPF (Figure 5.15; Table 5.3), and the stock steepness parameter (h) was calibrated at 0.83, indicating that 83% of pre-fishery recruitment (R_0) could be expected at 20% of virgin spawning stock. The recruitment mode (μ_1) was estimated in February, which agrees with the timing of the February survey designed for monitoring annual recruitment levels in this fishery. The mean carapace length at which 50% of the WKP population is vulnerable to the gear during fishing (l_f^{50}) and surveys (l_s^{50}) were 34.3 mm and 31.1 mm, respectively. Catchability (q) was estimated to peak in February, with a low in August and amplitude of 33%. Instantaneous natural mortality (M) was fixed using the GSV population estimate of 0.102 month^{-1} (Xiao and McShane, 2000a). No concerning correlations were evident among the key estimated parameters (Table 5.4), which indicates that the model was not over-parameterised and is symptomatic of a well-formulated model.

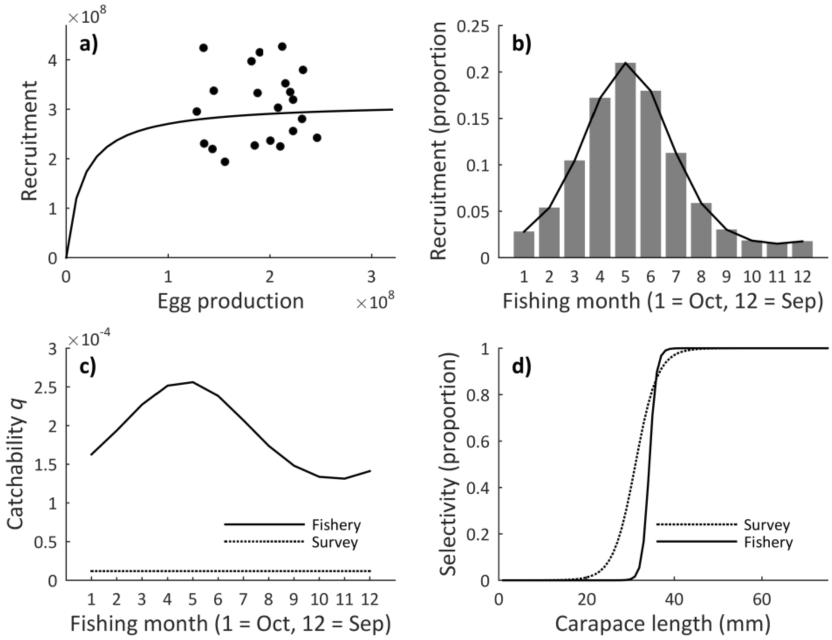

Figure 5.15. Predicted relationships for WKP in the SGPF: a) stock-recruitment relationship (based on 22 years of modelled stochastic recruitment, 1991—2013); b) recruitment pattern (proportion); c) fishery and survey catchability; and d) vulnerability at carapace length.

Table 5.3. Parameter estimates and standard errors for SGPF model calibration (NLL: Stage 1, -4604.1; Stage 2, -25.4). η_1 corresponds to the first year for estimating recruitment residuals (1991).

Parameter	Estimate	Standard error	Estimate transformed
ξ	2.944	0.060	0.833
Υ	1.094	0.012	2.986
μ_1	5.063	0.114	
κ	1.318	0.134	
l_s^{50}	31.121	0.148	
δ_s	0.395	0.045	
l_f^{50}	34.280	0.133	
δ_f	1.252	0.106	
ς	0.334	0.123	
ϑ	-0.054	0.097	
η_1	0.104	0.148	
η_2	0.052	0.145	
η_3	0.297	0.133	
η_4	0.007	0.125	
η_5	-0.161	0.101	
η_6	0.373	0.112	
η_7	0.539	0.133	
η_8	-0.131	0.127	
η_9	0.282	0.141	
η_{10}	0.417	0.107	
η_{11}	-0.200	0.122	
η_{12}	-0.067	0.118	
η_{13}	0.197	0.102	
η_{14}	0.353	0.089	
η_{15}	-0.169	0.089	
η_{16}	0.281	0.106	
η_{17}	0.060	0.089	
η_{18}	0.147	0.097	
η_{19}	0.372	0.096	
η_{20}	-0.053	0.086	
η_{21}	-0.192	0.106	
η_{22}	0.086	0.101	

Table 5.4. Correlation matrix of the ten leading model parameters estimated for the SGPF. Correlation strength increases with cell-shading intensity.

	ξ	Υ	μ_1	κ	l_s^{50}	δ_s	l_f^{50}	δ_f	ς	ϑ
ξ	1.00									
Υ	-0.88	1.00								
μ_1	0.06	0.29	1.00							
κ	-0.14	-0.07	-0.05	1.00						
l_s^{50}	0.15	-0.08	0.12	-0.17	1.00					
δ_s	-0.02	0.03	0.04	0.16	0.00	1.00				
l_f^{50}	-0.11	0.06	-0.04	0.02	-0.06	-0.05	1.00			
δ_f	0.11	-0.14	-0.05	0.07	-0.14	0.06	-0.02	1.00		
ς	0.16	-0.11	0.13	0.05	0.04	0.08	-0.20	0.09	1.00	
ϑ	-0.09	0.09	0.03	-0.03	-0.15	-0.13	0.03	-0.31	-0.03	1.00

5.2 Reference points

MSY and MEY reference point calculations were based on optimising the population and economic models through fishing mortality (proportional to effort). The results were highly dependent on the economic parameters (at different levels of fishing power) (Table 4.5; Table 4.6), and the status quo effort pattern and annual mean fleet effort between 2009 and 2013. Three to five sets of MSY and MEY optimisations were determined using the length-based model groups – one for status quo fishing power and the others for 5% increments in fishing power (up to 10% for the GSVPF and 20% for the SGPF). Assumptions for economic rates and best estimates of uncertainty for fixed and variable costs were made for the propagation of realistic confidence intervals, which should be considered with the mean estimates.

5.2.1 Gulf St Vincent Prawn Fishery

MSY and MEY for the GSVPF were estimated at ~370 t and ~320 t, respectively (Table 5.5), and maintained at these levels at 10% greater fishing power and associated costs expected with a reduction in the number of vessels. Negligible difference between MEY_{fv} (against fixed and variable costs) and MEY_{v} (against variable costs only) indicated that MEY was relatively insensitive to fixed costs. Fishing effort at MEY (E_{MEY}) ranged between 520 and 570 vessel-nights, with lower effort levels required at up to 10% greater fishing power. In comparison, mean annual fishing effort since 2009 was less than 50% of E_{MEY} (at ~260 vessel-nights) for harvests of 62% of MEY (~200 t).

Mean catch rate reference points, corresponding to MSY and MEY_{v}, and derived from monthly catchability and exploitable biomass estimates, were calculated to simulate within-year monitoring and management of fishing and surveys (Figure 5.16). There was some uncertainty around the (lack of a) seasonal pattern in these reference points, suggesting that it may be more informative to monitor the overall average or peak versus non-peak months. The mean fishery catch rates corresponding to MSY and MEY_{v} were ~380 kg block-vessel-night^{-1} and ~570 kg block-vessel-night^{-1}, respectively. The mean survey catch rate at MSY was 13.5 kg trawl-shot^{-1} (≈ 0.99 lb min^{-1}).

Table 5.5. Estimated management quantities (90% confidence intervals) at 2011/12 costs and different levels of fishing power (2011/12 fishing power = 1.00) in the GSVPF.

Quantities	Fishing power (proportion)		
	1.00	**1.05**	**1.10**
Harvest (t)			
MSY	368 (351 : 385)	368 (351 : 385)	368 (351 : 385)
MEY_{fv}	322 (297 : 345)	323 (297 : 347)	324 (297 : 345)
Effort (vessel-nights)			
E_{MEYfv}	573 (502 : 646)	551 (479 : 620)	528 (460 : 588)

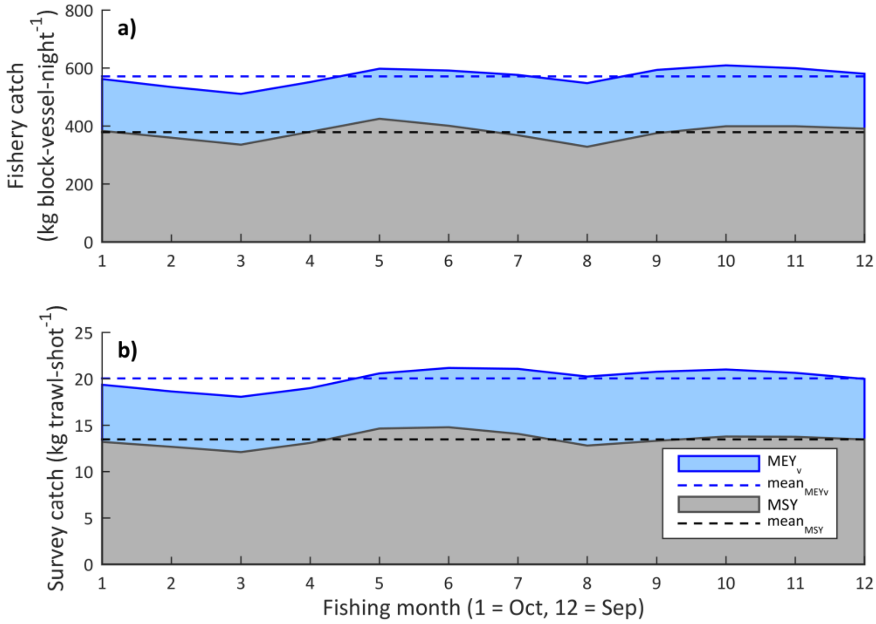

Figure 5.16. Mean monthly a) fishery and b) survey catch rate targets for the GSVPF at MSY and MEY$_v$. Catch rates were standardised to 2011/12 fishing power.

5.2.2 Spencer Gulf Prawn Fishery

MSY was estimated at ~2740 t for the SGPF and, at 2012/13 fishing power, MEY was ~2170 t (Table 5.6). With increases in fishing power up to 20%, MEY estimates increased to ~2230 t and E_{MEYfv} reduced from ~3190 to 2790 vessel-nights. In comparison, mean annual fishing effort for the last five fishing years (2009—2013) was less than 60% of E_{MEY} (at ~1820 vessel-nights) for harvests slightly more than 80% of MEY (~1820 t). Only minor differences were found between MEY$_{fv}$ and MEY$_v$, indicating that MEY was relatively insensitive to fixed costs.

The monthly catch rate reference points for MSY and MEY$_v$ are shown in Figure 5.17. Fishery catch rates corresponding to MSY indicate the biological limit of sustainable fishing; these limits ranged between 290 kg block-vessel-night^{-1} (November) and 500 kg block-vessel-night^{-1} (February). Fishery catch rates corresponding to MEY$_v$ ranged between 540 kg block-vessel-night^{-1} (August) and 870 kg block-vessel-night^{-1} (February). Survey catch rates at MSY ranged between 19.5 kg trawl-shot^{-1} (≈ 1.43 lb min^{-1}; December) and 32.1 kg trawl-shot^{-1} (≈ 2.35 lb min^{-1}; April).

Table 5.6. Estimated management quantities (95% confidence intervals) at 2012/13 costs and different levels of fishing power (2012/13 fishing power = 1.00) in the SGPF.

Quantities	**Fishing power (proportion)**				
	1.00	**1.05**	**1.10**	**1.15**	**1.20**
Harvest (t)					
MSY	2741 (2714 : 2768)	2741 (2714 : 2768)	2741 (2714 : 2768)	2741 (2714 : 2768)	2741 (2714 : 2768)
MEY_{fv}	2176 (1976 : 2341)	2190 (1996 : 2355)	2201 (2017 : 2362)	2213 (2011 : 2369)	2225 (2034 : 2372)
Effort (vessel-nights)					
E_{MEYfv}	3188 (2633 : 3762)	3082 (2545 : 3633)	2977 (2487 : 3536)	2878 (2368 : 3359)	2789 (2300 : 3246)

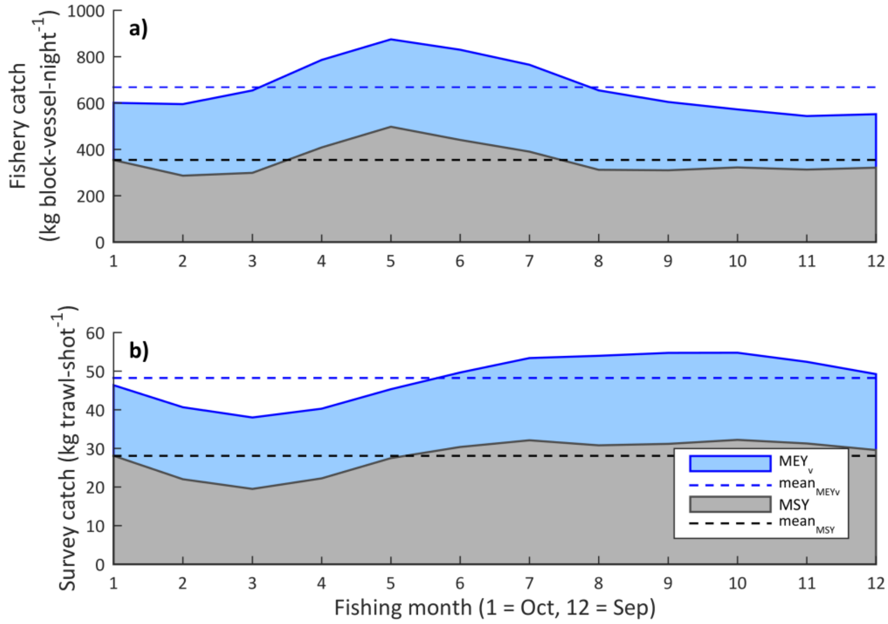

Figure 5.17. Mean monthly a) fishery and b) survey catch rate targets for the SGPF at MSY and MEY_v. Catch rates were standardised to 2012/13 fishing power.

5.3 Simulation of management procedures

5.3.1 Gulf St Vincent Prawn Fishery

The results (median values) of management procedure (MP) simulations for the GSVPF (listed in Table 4.13) over ten future years compared to MP1 (status quo) are summarised as follows (see Figure 5.18 for uncertainties represented by boxplots).

MP1 (status quo: 10 vessels, 260 vessel-nights, 40 t pre-Christmas catch cap, and fishing in November, December and March–June)

- Expected annual harvests were 211 t over 260 vessel-nights.
- Predicted fishery catch rates were 778 kg block-vessel-night^{-1}, while survey catch rates were 26.2 kg trawl-shot^{-1}.
- Median carapace length was 39.8 mm, while the size-grade category distribution was left-skewed with a median of 3.28 (see Figure 5.13 for category definitions).

MP2 (7 vessels)

- A reduction in the number of vessels from 10 (status quo) to 7 resulted in a small increase in fishery catch rates to ~815 kg block-vessel-night^{-1}.
- Egg production and exploitable biomass were not significantly reduced, yet the NPV_{fv} and $profit_{fv}$ (relative to fixed and variable costs) over 10 years increased by ~60% and ~35%, respectively.

MP3 (5 vessels)

- Of all the management procedures simulated, a reduction in the number of vessels from 10 (status quo) to 5 resulted in the highest fishery catch rates at ~840 kg block-vessel-night^{-1}.
- Egg production and exploitable biomass were not significantly reduced, yet the NPV_{fv} and $profit_{fv}$ (relative to fixed and variable costs) over 10 years increased by ~100% and ~55%, respectively.
- While the economic returns ranked second after MP6 (see below), MP3 was considered to perform better overall, owing to higher predicted catch rates, and higher levels of egg production and exploitable biomass (see Figure 5.18 for the trajectory of $profit_{fv}$ and other selected performance measures over ten future years for this ‘best’ performing procedure).

MP4 (7 vessels and 300 vessel-nights)

- An increase in effort to 300 vessel-nights with 7 vessels yielded an increase in harvest of ~245 t, and at a slightly higher catch rate.
- Small reductions occurred in egg production and exploitable biomass.
- NPV_{fv} and $profit_{fv}$ were ~80% and ~45% greater than status quo, respectively.

MP5 (7 vessels and 350 vessel-nights)

- An increase in effort to 350 vessel-nights with 7 vessels yielded an increase in harvest of ~270 t, but at a slightly reduced catch rate.
- Egg production and exploitable biomass reduced by almost 10%.
- NPV_{fv} and $profit_{fv}$ were ~95% and ~55% greater than status quo, respectively.

MP6 (7 vessels and 400 vessel-nights)

- An increase in effort to 400 vessel-nights with 7 vessels yielded an increase in harvest of ~300 t (43% greater than status quo), but at a reduced catch rate. Fishery catch rate was the lowest of all procedures, at ~720 kg block-vessel-night^{-1} (7% less than status quo).
- Survey catch rate, egg production and exploitable biomass for MP6 were the lowest of all management procedures. All three measures were at least 10% less than status quo.
- The best economic returns were obtained for MP6. NPV_{fv} and $profit_{fv}$ were ~115% and ~65% greater than status quo, respectively.
- With an expected increase in harvest for MPs 4 to 6, a negative relationship was evident between profit and egg production or exploitable biomass.

MP7 (7 vessels and 60 t pre-Christmas catch cap)

- A 20 t increase in the pre-Christmas catch cap did not have any adverse impact on egg production.
- Compared to MP2, there were no significant changes in performance measures, although fishery catches were slightly higher and the second highest (after MP3).

MP8 (7 vessels and alternate closure of upper/lower gulf)

- Alternating closure of the upper and lower gulf midway through the fishing year resulted in narrower size distributions (carapace length and size-grade category).
- Other than improved size selectivity, performance measures for MP8 were similar to MP2.

MP9 (7 vessels, 180 t quota, no limit on effort, and fishing all months)

- With a quota of 180 t, MP9 was the only management procedure with less harvest than status quo, and to result in increases (albeit small) in egg production and exploitable biomass.
- Survey catch rate was the highest of all management procedures at 27.6 kg trawl-shot^{-1}.
- Despite increases in fishery and survey catch rates, MP9 resulted in the least economic returns of all management procedures (see Figure 5.18 for the trajectory of $profit_{fv}$ and other selected performance measures over ten future years for this 'worst' performing procedure). Relative to variable costs only, NPV_v and $profit_v$ were less than status quo.

MP10 (7 vessels, 200 t quota, no limit on effort, and fishing all months)

- Compared to MP4, in which harvests of ~245 t were predicted over 300 vessel-nights, MP10 required more effort to obtain similar harvest under quota arrangements, with fishery catch rate being the second lowest (after MP6).
- MP10 performed similarly to MP4 for most of the other measures.
- Broader size distributions (carapace length and size-grade category) were expected under both quota settings (MP9 and MP10) than the other effort-limited management procedures.

General comments on performance measures:

- A change in harvest from status quo resulted in a change in exploitable biomass in the opposite direction, but not necessarily by the same magnitude.
- The percentage change for exploitable biomass, survey catch rate and egg production from status quo were approximately equal, except for MP8, where survey catch rate was reduced by 8% with no change in biomass or egg production;
- There was no significant change in median carapace length and size-grade category among the management procedures; all differences were within ±2% of status quo.
- All management procedures demonstrated improvements in economic performance, except MP9, where NPV_v and $profit_v$ were 8-9% less than status quo.

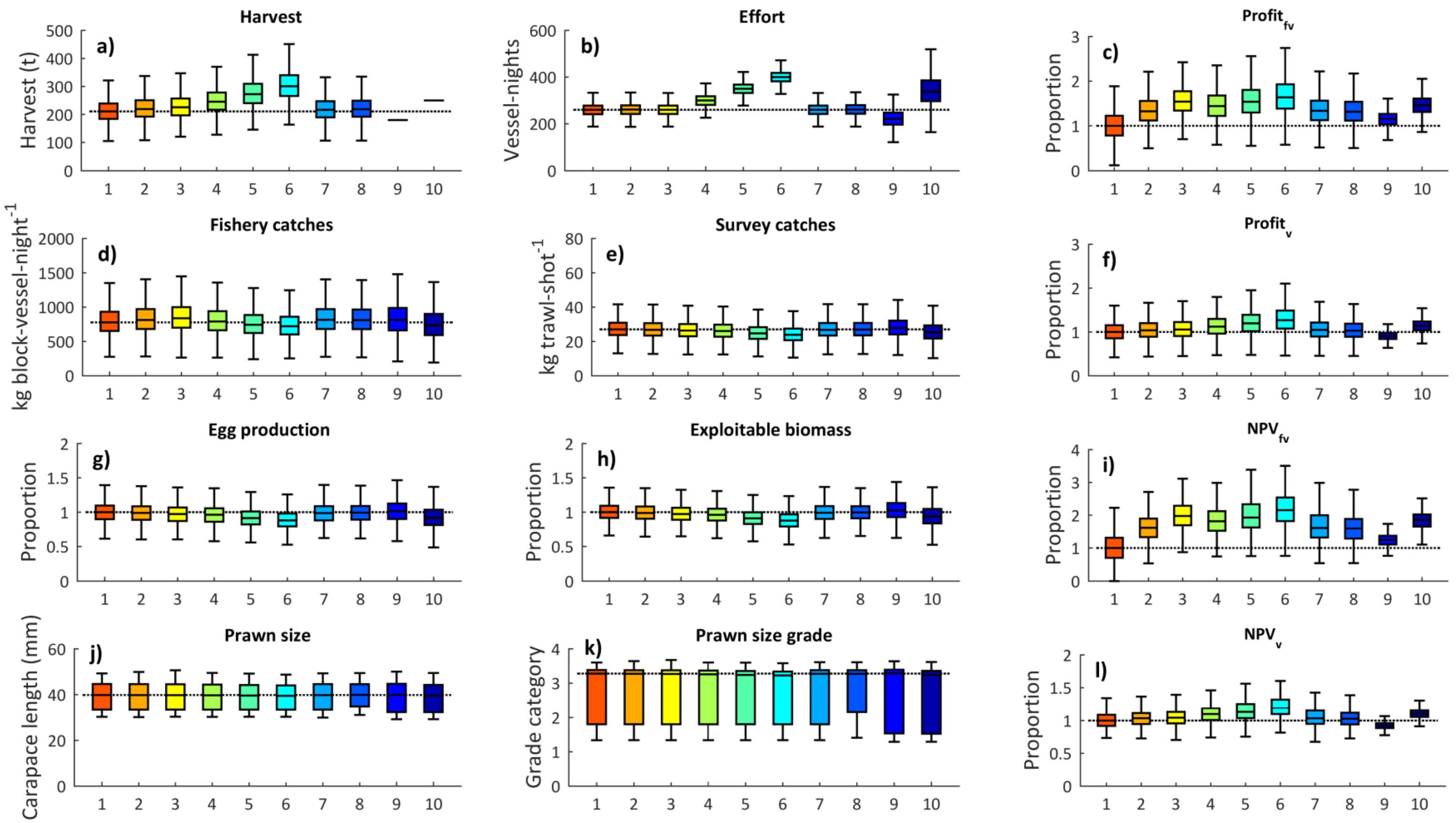

Figure 5.18. Performance measures over ten future years (2014—2023) for ten different WKP management procedures (MPs) for the GSVPF (Table 4.13). Plots a) and b) represented industry functioning, plots d), e), j) and k) represented the main performance indicators used in the current management plan (Dixon and Sloan, 2007), plots g) and h) measured population change, and plots c), f), i) and l) (last column of plots) indicated economic conditions. The dotted reference line indicates the median (= 1 or estimated value) for MP1 (status quo). The plots display the simulated distributions (1000 samples) around their medians (solid line in middle of each box). The bottom and top edges of each box are the 25th and 75th percentiles, and the whiskers indicate ~95% coverage of the simulation estimates.

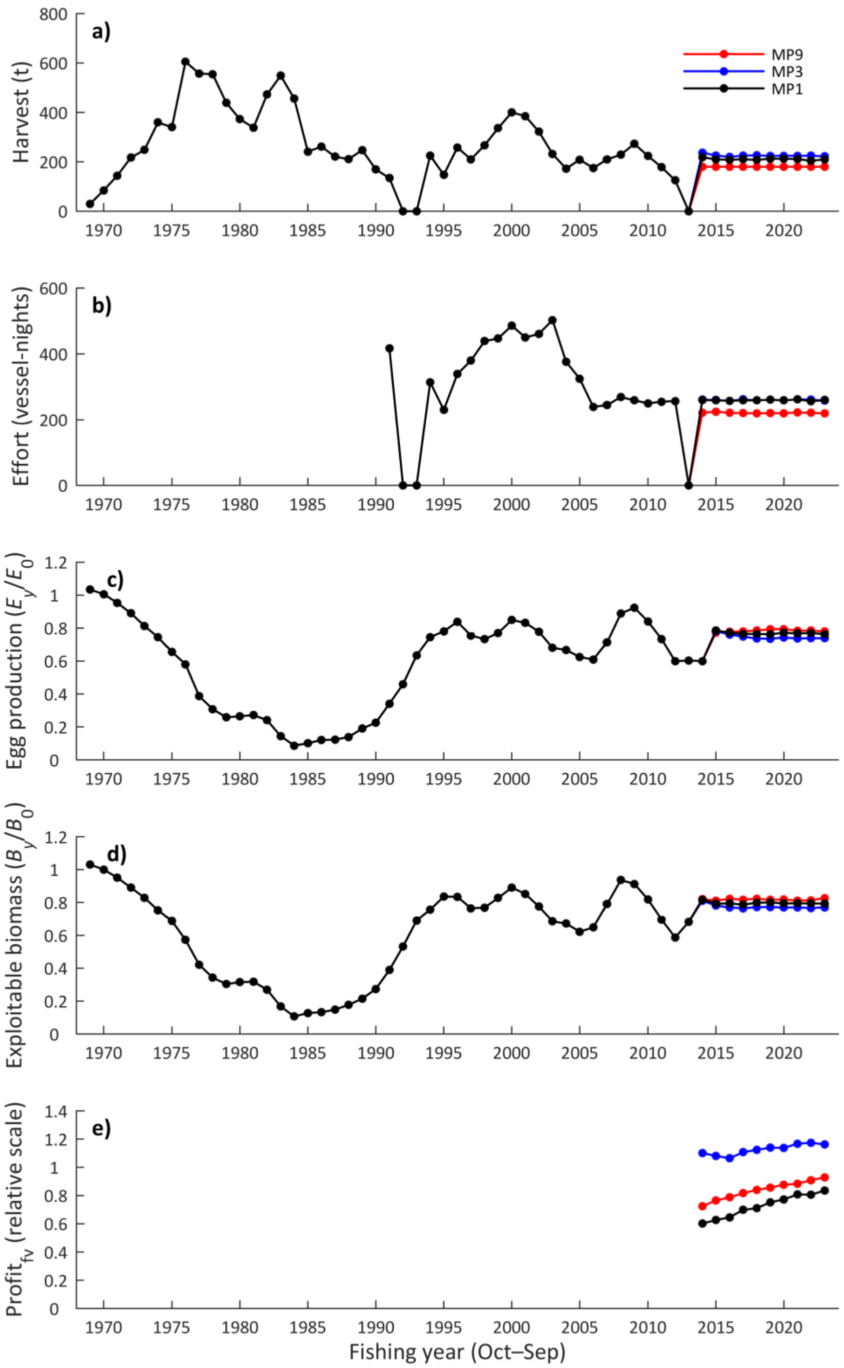

Figure 5.19. Annual time series of selected performance measures for the GSVPF from 1969—2023 (including simulations of three management procedures from 2014—2023, where the median is plotted). Performance measures: a) harvest; b) effort; c) egg production relative to virgin estimate; d) exploitable biomass relative to virgin; and e) relative profit$_{fv}$. Management procedures: MP1, status quo; MP3, 5 vessels ('best'); MP9, 7 vessels and 180 t quota ('worst'). Note: effort data was not available prior to 1991 and profit$_{fv}$ was only estimated for ten future years.

5.3.2 Spencer Gulf Prawn Fishery

The results (median values) of management procedure simulations for the SGPF (listed in Table 4.14) relative to MP1 (status quo) are summarised as follows (see Figure 5.20 for uncertainties represented by boxplots):

MP1 (status quo: 39 vessels, 2000 vessel-nights, pre-Christmas catch cap decision rules, and fishing in November, December and March–June)

- Expected annual harvests were ~1650 t over 2000 vessel-nights.
- Predicted fishery catch rates were 882 kg block-vessel-night^{-1}, while survey catch rates were 58.9 kg trawl-shot^{-1}.
- Median carapace length was 40.4 mm and median size-grade category was 3.30 (see Figure 5.13 for category definitions).

MP2 (33 vessels)

- With the same level of effort as status quo, a reduction in the number of vessels to 33 resulted in slight (~2-3%) increases in harvest (~1680 t) and fishery catch rate.
- The slight increase in harvest resulted in ~10% increase in NPV_{fv} and $profit_{fv}$ (relative to fixed costs), while egg production and exploitable biomass were not significantly reduced.

MP3 (30 vessels)

- A reduction in the number of vessels to 30 resulted in small (~5-6%) increases in harvest (~1730 t) and fishery catch rate.
- An increase in harvest resulted in ~15% increases in NPV_{fv} and $profit_{fv}$ (relative to fixed costs), while egg production and exploitable biomass were not significantly reduced.

MP4 (20 vessels, no pre-Christmas catch cap, and fishing all months)

- Of all the management procedures simulated, predicted harvest was greatest for MP4 at ~1940 t when the size of the fleet was halved (to 20 vessels), and pre-Christmas catch cap and fishing month restrictions were removed.
- The best economic returns were obtained for MP4; NPV_{fv} and $profit_{fv}$ were 60% and 40% higher than status quo, respectively (see Figure 5.20 for the trajectory of $profit_{fv}$ and other selected performance measures over ten future years for this ‘best’ performing procedure).
- Egg production and exploitable biomass were the lowest of the management procedures at ~10% less than status quo.

MP5 (12 vessels, no pre-Christmas catch cap, and fishing all months)

- Although a reduction in the number of vessels to 12 in the SGPF is unlikely, MP5 was included to broaden the range of fleet sizes and thereby enable performance to be estimated for management procedures with fleet sizes intermediate to those simulated.
- The highest fishery catch rate was predicted for MP5 at 1050 kg block-vessel-night^{-1}, and profits were second highest (after MP4).
- Although catch rates and profits were relatively high, 12 vessels were unable to reach status quo effort and harvest levels, with only ~1200 vessel-nights fished (60%) for a harvest of less than 1400 t (84%).

MP6 (fishery closed November)

- Closure of the fishery in November did not increase egg production; it actually reduced egg production by 5%.
- Reduced egg production is likely to be attributed to the redistribution of effort to higher catch-rate months, resulting in increased harvests and reduced exploitable biomass.
- All economic performance measures increased by 10-20%.

MP7 (pre-Christmas catch cap reduced by 40%)

- Reducing the pre-Christmas catch cap by 40% did not significantly increase egg production.
- Annual harvests were reduced by ~100 t, and economic returns were equal worst (with MP8 and MP11) of all management procedures, with NPV and profits reduced by ~10% (see Figure 5.20 for the trajectory of $profit_{fv}$ and other selected performance measures over ten future years for this 'worst' performing procedure).
- There were no significant changes in the remaining performance measures; all other differences were within ±2%.

MP8 (fishery closed March)

- Closure of the fishery in March did not significantly increase exploitable biomass, nor did it have any effect on prawn size.
- Redistribution of effort to other months resulted in reduced harvests by ~100 t and equal worst economic performance (with MP7 and MP11), with NPV and profits reduced by ~10%.
- All performance measures were similar to those for MP7.

MP9 (fishery closed June and pre-Christmas catch cap increased by 190 t)

- Offsetting closure of the fishery in June by adding the same tonnage (190 t) to the pre-Christmas catch cap did not significantly impact egg production.
- Due to the higher prices paid at Christmas, NPV and profits increased by ~10%.

MP10 (northern gulf closed March)

- Closure of northern gulf in March did not have any effect on exploitable biomass or prawn size.
- There were no significant changes in any performance measures from status quo; all differences were within ±2%.

MP11 (fishery closed March and northern gulf closed April)

- Closure of the fishery in March and the northern gulf in April did not significantly increase exploitable biomass, nor did it have any effect on prawn size.
- Redistribution of effort to other months resulted in reduced harvests by ~100 t and the equal worst economic performance (with MP7 and MP8), with NPV and profits reduced by ~10%.

MP12 ('North End' closed November and December)

- Closure of the 'North End' of the Gutter region did not result in increased egg production.
- There were no significant changes in any performance measures from status quo; all differences were within ±2%.

MP13 (1950 t quota, no limit on effort, and fishing all months)

- Despite a quota setting of 1950 t, the predicted harvest only reached 1750 t.
- An increase in harvest (relative to status quo) resulted in increased NPV and profits, but reduced catch rates, egg production and exploitable biomass were also predicted.
- Fishery and survey catch rates under a 1950 t quota were relatively low at 797 kg block-vessel-night^{-1} and 56.7 kg trawl-shot^{-1}, respectively.

MP14 (2200 t quota, no limit on effort, and fishing all months)

- Despite a quota setting of 2200 t, the predicted harvest only reached 1950 t.
- An increase in harvest (relative to status quo) resulted in increased NPV and profits, but reduced catch rates, egg production and exploitable biomass were also predicted.
- Fishery and survey catch rates under a 2200 t quota were the lowest of all management procedures at 757 kg block-vessel-night^{-1} and 54.2 kg trawl-shot^{-1}, respectively.

General comments on performance measures:

- A change in harvest from status quo resulted in a change in exploitable biomass in the opposite direction, but not necessarily by the same magnitude.
- The percentage change for exploitable biomass, survey catch rates and egg production from status quo were approximately equal;
- There was no significant change in median carapace length and size-grade category among the management procedures; all differences were within ±2% of status quo.

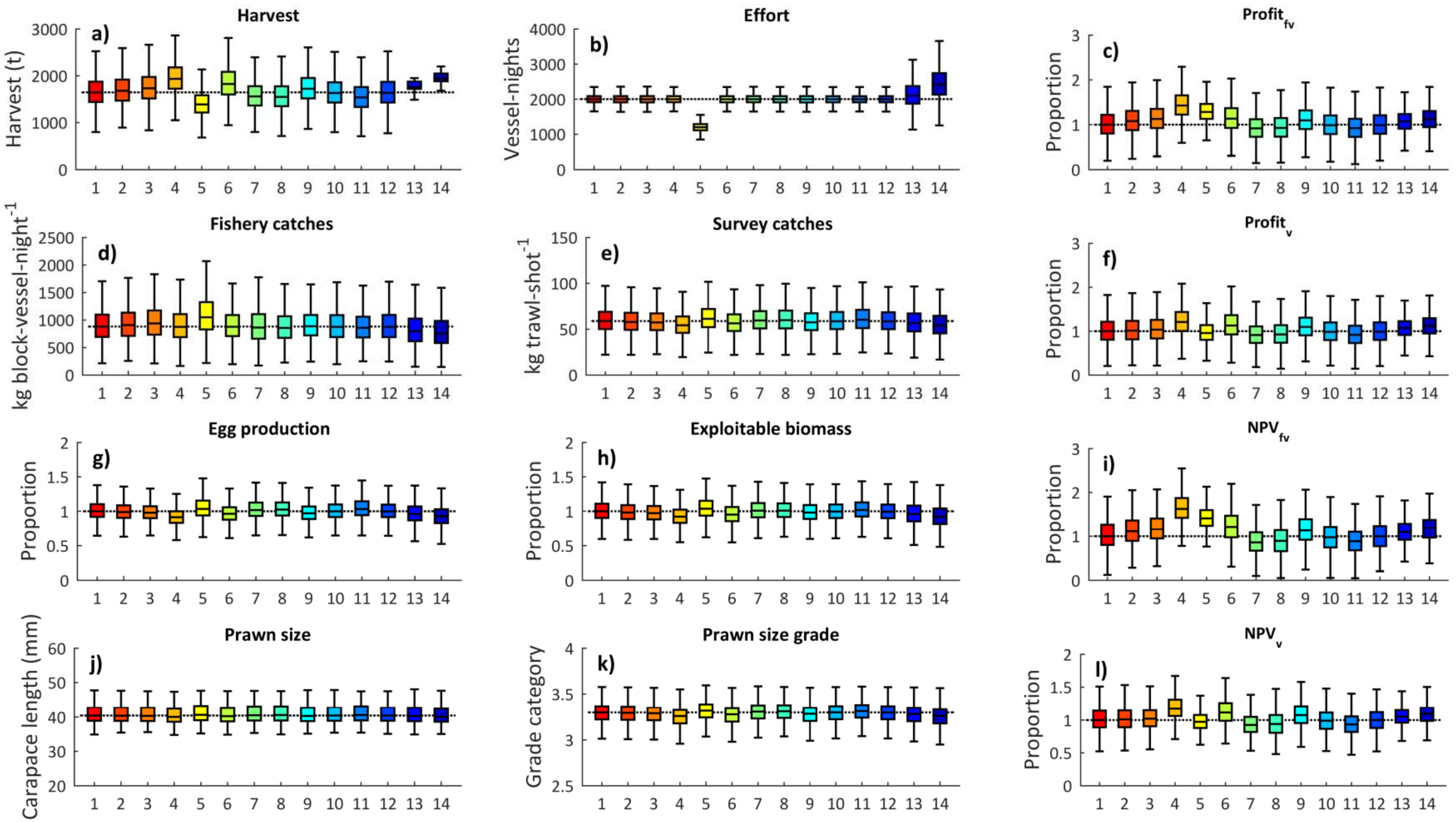

Figure 5.20. Performance measures over ten future years (2014—2023) for 14 different WKP management procedures (MPs) for the SGPF (Table 4.14). Plots a) and b) represented industry functioning, plots d), e), j) and k) represented the main performance indicators used in the current management plan (PIRSA, 2014), plots g) and h) measured population change, and plots c), f), i) and l) (last column of plots) indicated economic conditions. The dotted reference line indicates the median (= 1 or estimated value) for MP1 (status quo). The plots display the simulated distributions (1000 samples) around their medians (solid line in middle of each box). The bottom and top edges of each box are the 25th and 75th percentiles, and the whiskers indicate ~95% coverage of the simulation estimates.

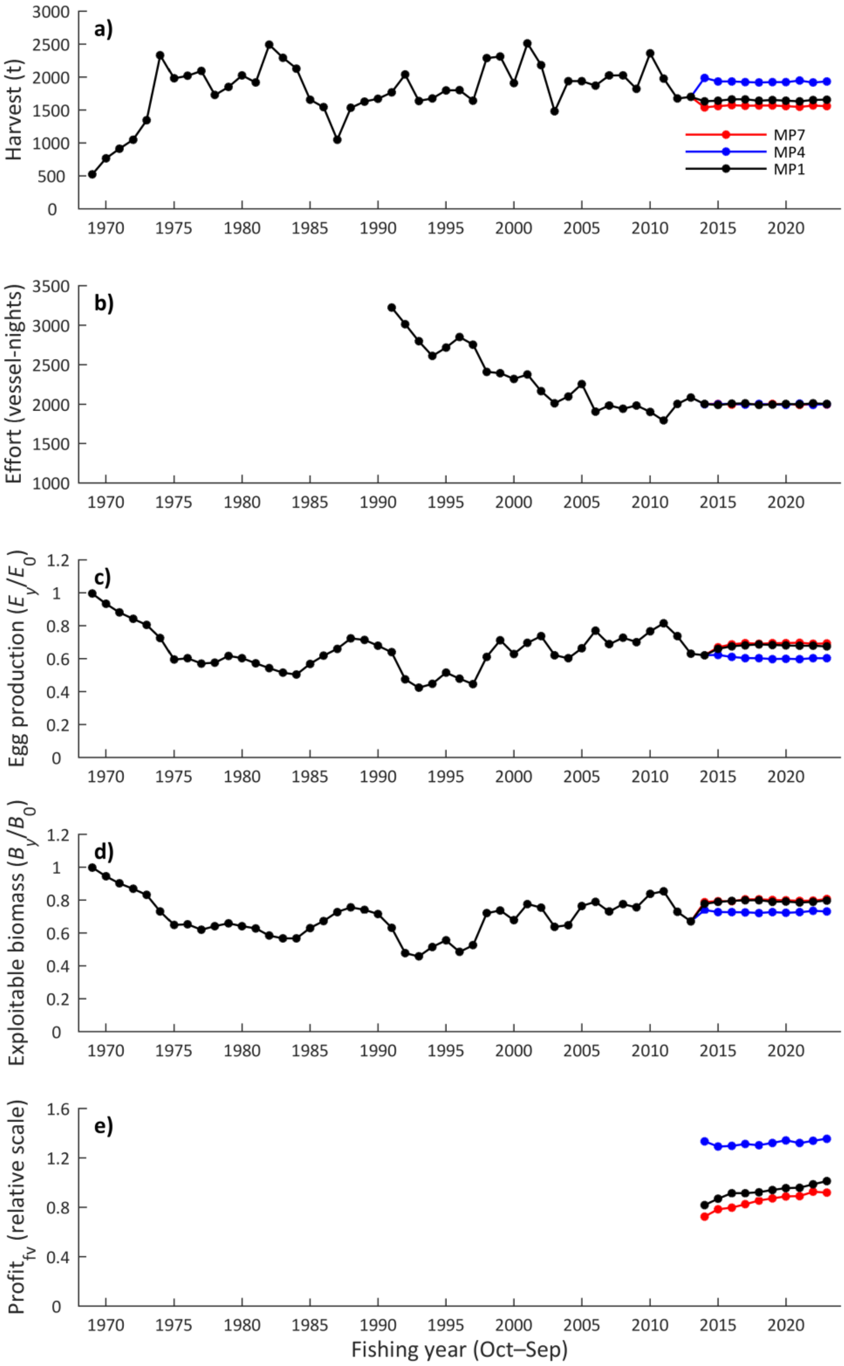

Figure 5.21. Annual time series of selected performance measures for the SGPF from 1969—2023 (including simulations of three management procedures from 2014—2023, where the median is plotted). Performance measures: a) harvest; b) effort; c) egg production relative to virgin estimate; d) exploitable biomass relative to virgin; and e) relative profit$_{fv}$. Management procedures: MP1, status quo; MP4, 20 vessels; MP7, pre-Christmas catch cap reduced by 40%. Note: effort data was not available prior to 1991 and profit$_{fv}$ was only estimated for ten future years.

6 Discussion

The analyses and preliminary findings of this project represent an important advance in the stock assessment of WKP in South Australia's GSVPF and SGPF with respect to improving their profitability. Through the integration of standardised catch histories, information on WKP biology, recent economic data for both fisheries, and established theories and principles in fishery population dynamics, the first bio-economic model has been developed for these fisheries. It is based on the model recently developed for the EKP fishery of New South Wales and Queensland, the outputs of which have been successfully used to assess the status and management of that fishery. The main outputs of the South Australian model are the WKP population and economic status for the GSVPF and SGPF, and evaluation of simulated management procedures. For the latter, the performance of a range of fishery-specific management procedures that are currently of interest to fishery managers and industry were evaluated. The results also include reference points that help to determine the status of each fishery relative to MSY and MEY.

6.1 Models and data

Overall, the model fits to the fishery input data were relatively good. The fits to both fishery and survey catch rates were typical for modelling fishery catches, although those for the SGPF were measurably better than the GSVPF. Moreover, the agreement between fishery and survey catch rates were much closer for the SGPF. The fits to length-frequency data for both fisheries were also good, thus indicating that the length-based model performed well, within the constraints of the data (see Section 6.4 for caveats surrounding the data, particularly the size-transition matrix estimator). Similarly, the fits to size grade data were also good. Based on these model-fitting attributes, the length-based model was representative of the observed size structures in the extensive (compared to most fisheries) surveys and size grade data.

An important output from modelling the WKP populations in the GSVPF and SGPF was the stock steepness parameter, which defines the relationship between annual spawning (egg production) and recruitment to the fishery in the following year. Our estimates of steepness for WKP were 0.60 for the GSV stock and 0.83 for the SG stock; however, these are provisional estimates as more work is required on the standardisation of catches and size-transition matrices (see Further development, Section 8). Nevertheless, as a comparison, Ye (2000) reported steepness values of 0.23-0.52 in a meta-analysis of 13 penaeid prawn stocks, while other estimates in Australia have ranged from 0.26-0.36 for tiger prawns in the NPF (Dichmont *et al.*, 2001), 0.36 for the EKP along the east coast of New South Wales and Queensland (O'Neill *et al.*, 2014), and 0.46 for tiger prawns in the Torres Strait (O'Neill and Turnbull, 2006). Steepness is equivalent to the recruitment compensation ratio (Goodyear, 1977), which represents the extent to which recruitment per spawner can increase to compensate for a depleted spawning stock. The higher estimates of steepness in this study is reasonable given the cooler climate and slower growth of WKP than the tropical and subtropical penaeids, and suggests that WKP recruitment in the GSVPF and SGPF is relatively resilient to low levels of egg production. As an example, the GSV spawning stock was estimated to be particularly low for several years before the 1992—1993 closure at 10-20% of its virgin state, yet recruitment levels were maintained at 40-50% over the same period. No concerning correlations were evident among the key estimated parameters, which indicate that the models were not over-parameterised.

6.2 Reference points

Since the introduction of MEY policy for Australia's Commonwealth fisheries in 2007 (Australian Government, 2007), there has been a growing appreciation within South Australian fisheries of the concept of maximising profit without needing to maximise sustainable yields, including fisheries managed primarily with input controls. The GSVPF and SGPF are two such fisheries that have acknowledged this need over the past several years in which they have faced significant challenges of increasing fuel prices and competition from cheaper imported aquaculture prawns. In this study, MSY and MEY estimates for both fisheries were obtained by simulation of WKP fishery dynamics and, as is typically found, MEY estimates were substantially less than MSY. Grafton *et al.* (2007) identified that this ratio (of MEY to MSY) would decrease further at higher fishing costs and/or lower product prices.

The very flat nature of the stock-recruitment relationships suggests that there is little information about the dependence of recruitment on egg production. Since the estimation of MSY and MEY follow closely from the stock-recruitment relationship, it would be reasonable to question the reliability of these inferred estimates. Therefore, whilst the model is able to produce estimates of MSY and MEY, which are presented in this report, these estimates should be treated as provisional and demonstration of some of the key outputs from the model.

6.2.1 Gulf St Vincent Prawn Fishery

For the GSVPF, MSY was estimated at ~370 t. Due to the high estimate of stock steepness, high levels of effort at MSY (E_{MSY}) were estimated, but these were not considered relevant to current management of the fishery. Uncertainty surrounding E_{MSY} is not unusual in fisheries assessments, and emphasises that this limit should not be approached as it leads to diminishing profits and increasing risk of overfishing (Garcia and Staples, 2000). MEY estimates of ~320 t for the GSVPF were influenced by the reported high variable costs of fishing. In the absence of detailed information on fishing power, we set a 10% increase in fishing power, vessel and fuel costs with the removal of up to 5 vessels (50%) from the fleet. At this higher fishing power, less effort was required to achieve MEY (E_{MEY}: ~570 vessel-nights down to ~520 vessel-nights), but MEY estimates themselves did not change.

Catch rate reference points corresponding to MSY and MEY for the GSVPF were ~380 and ~570 kg block-vessel-night^{-1}, respectively. Catch rates above these points indicate that the exploitable biomass (B_{curr}) is greater than the biomass at MSY (B_{MSY}). As a comparison, the at-sea decision rules of the current harvest strategy (Dixon and Sloan, 2007) require closure of areas or cessation of fishing if average nightly catches over two consecutive nights fall below 350 kg in November/December or 450 kg from March—June. Although the current rules are less conservative, a retrospective comparison of the mean monthly catch rates with these reference points confirmed a reduced stock in 2012. These observations suggest that, under the current level of fishing power (related to fleet size) and fishing pattern, the reference points for MSY and MEY may be more appropriate catch criteria.

6.2.2 Spencer Gulf Prawn Fishery

MSY for the SGPF was estimated at ~2740 t. Increases in fishing power, vessel and fuel costs by up to 20% required 14% less effort to achieve MEY than status quo (E_{MEYfv}: ~3190 vessel-nights down to ~2790 vessel-nights); MEY estimates increased marginally (by ~2%).

Monthly catch rate reference points corresponding to MSY for the SGPF ranged between 290 and 500 kg block-vessel-night^{-1}, and the MEY reference points ranged between 540 and 870 kg block-vessel-night^{-1}. The minimum fleet catch rate of the current harvest strategy is generally more conservative at 350-600 kg, depending on month and region of the gulf (PIRSA, 2014). Nevertheless, retrospective comparison of month-specific reference points to mean fishery catch rates indicated that $B_{curr} > B_{MSY}$ since 1991.

Up to now, the stock status of the GSVPF or SGPF has been determined using a weight-of-evidence approach, and, recently for the SGPF (Noell *et al.*, 2014), estimated proxies for B_{MSY} and B_{MEY}. Despite the inability to previously estimate MSY and MEY (without a bio-economic model), it appears the current empirical reference points have been effective in management. This is most likely to have been the result of a combination of: 1) an effective harvest strategy, in which surveys are conducted prior to fishing to identify areas of target-sized prawns and acceptable abundance; 2) real-time monitoring of prawn size and catch rates by the fleet; and 3) conservative limits on input (e.g. number of fishing nights) and output controls (e.g. pre-Christmas fleet catch cap for the SGPF).

6.3 Management procedures

The average number of nights fished in recent years was 26 per vessel in the GSVPF and 51 per vessel in the SGPF. These relatively low levels of effort suggested testing a strategy of reduced vessel numbers. We tested several strategies. The set of management procedure simulations for each fishery encompassed a broad spectrum of strategies developed in consultation with fisheries managers and industry representatives. Specifically, they simulated the effects of reducing the numbers of vessels, increasing total effort, modifying harvest levels during the peak spawning period (November/December), temporal and spatial closures, and implementing harvest quotas. These procedures represented the culmination of ideas and discussions that had taken place with these stakeholder groups over the past few years.

Assuming the parameter estimates and uncertainties were realistic, all management procedures were predicted to be biologically sustainable. However, despite our best estimates of variability of stock parameters for modelling WKP population dynamics, this may not always safeguard against unpredictable stock behaviour. Therefore, a holistic approach was used in evaluating each management procedure, where we not only took into account the predicted change in catch rates and economic performance measures from status quo, but also interpreted changes in exploitable biomass and egg production as relative indicators to the stock.

6.3.1 Gulf St Vincent Prawn Fishery

Two recently conducted independent reviews for the GSVPF (Knuckey *et al.*, 2011; Morgan and Cartwright, 2013) indicated that the operation of 10 vessels in the fishery is unlikely to be economically viable in the foreseeable future. Following on from the recommendations of these reviews, the GSVPF is currently being managed under individual transferable effort (tradable nights) arrangements to enable amalgamation of nights, the aim of which is to remove vessels and excess capacity before the planned next step of introducing individual transferrable quotas (ITQs). This management direction taken by the fishery influenced the specifications of the management procedures developed. All simulated management procedures included a reduction in the number of vessels (other than status quo), and two of these included quota.

Of the management procedures simulated for the GSVPF, MP3, with a reduction in the fleet size to 5 vessels, performed best in terms of increased NPV_{fv} (by ~100%), $profit_{fv}$ (by ~55%) and fishery catch rates from status quo. These are large and important potential increases in profitability highlighted by the model outputs, and are in accord with the logic that a fishery (such as the GSVPF) that uses its vessels less than 10% of the year is over-capitalised and therefore economically underperforming. The vessel-reduction strategy currently being pursued in this fishery make perfect sense in terms of reducing this seemingly over-capitalisation to produce a more efficient operation and realise some of these projected gains. Although MP6, with a fleet size of 7 vessels and total effort of 400 vessel-nights, resulted in greater NPV_{fv} and $profit_{fv}$ than MP3, significant reductions in exploitable biomass and egg production were also predicted (unlike MP3, where there were no changes in these measures). The implementation of harvest quotas in MP9 and MP10 did not appear to offer any clear advantages to the other management procedures that were tested. Economic performance measures were at their lowest for MP9, with a quota of 180 t, and NPV_v and $profit_v$ were less than status quo despite a smaller fleet size. MP10 fared better with a quota of 250 t, although when compared with MP4, where similar harvests were predicted with the same number of vessels (7), effort was relatively high and variable and prawn size was smaller for no additional economic return.

6.3.2 Spencer Gulf Prawn Fishery

It was relatively difficult to identify the best performing management procedure for the SGPF. Of all the management procedures simulated, all four economic performance measures were highest (e.g. NPV_{fv} and $profit_{fv}$ were 60% and 40% greater than status quo) for MP4, where the number of vessels was reduced to 20 and the pre-Christmas catch cap was removed; however, exploitable biomass and egg production were marginally lower. This management procedure would also require significant resources and planning to finance the removal of vessels; these costs were not factored into the economic component of the simulations. Consideration should also be given to the social implications for reducing the number of vessels (Sloan *et al.*, 2014; Triantafillos *et al.*, 2014).

Among the other management procedures, MP2 (33 vessels), MP3 (30 vessels), MP6 (November closure) or MP9 (June closure plus an increase in the pre-Christmas catch cap) appeared to offer reasonable compromises between increases in profit_{fv} and NPV_{fv} in the order of 10-20%, increases or no change in fishery catch rates, and reductions in exploitable biomass and egg production of less than 5%. Of these four alternatives, MP6 or MP9 would be more straightforward, immediate and cost-effective to implement than the removal of vessels under MP2 or MP3 (and for a similar outcome). As for the GSVPF, the implementation of ITQs in the SGPF did not appear to offer any additional benefit to some of the effort-limited procedures. Compared to MP6 and MP9, a quota of 1950 t for MP13 was predicted to fare worse with respect to every performance measure, and while a quota of 2200 t for MP14 resulted in similar economic performance, it was at the cost of substantially higher levels of effort (i.e. 20%) at lower fishery catch rates, and reductions in exploitable biomass and egg production.

6.3.3 Overview of simulations

In general, we found that economic performance improved with fewer vessels (until there were too few vessels to fish at status quo effort levels for the fleet, e.g. MP5 for the SGPF) and, for the GSVPF, as effort approached E_{MEY}. Unlike the GSVPF, variations in total fleet effort were not contemplated in the development of management procedures for the SGPF. However, preliminary estimates of MEY and E_{MEY} in this study suggest that greater profits for the SGPF may be possible at higher levels of effort, but would need to be evaluated by simulation.

Of the management procedures tested, there was no evidence to suggest that quota was the best way forward for either fishery. However, as the primary purpose of the project was to develop the model and not to test an exhaustive number of management procedures, these results do not necessarily rule out quota for future management. Rather, they demonstrate a limited comparison of specific management procedures, and any changes to these specifications should be separately evaluated. For example, the 180 t and 250 t quotas examined for the GSVPF are considerably less than the estimated mean MEY, so while the economic performance measures for these management procedures fared relatively poorly, they may not be indicative of a fully-utilised resource. While the transition to ITQs (currently being considered for the GSVPF) may help to ensure that profits are not dissipated through 'race to fish' behavior and over-capitalisation, estimates of harvest targets such as MEY can be highly variable. Updating the model and obtaining revised estimates are also time demanding, which presents the challenge of estimating MEY within a timeframe that is relevant to WKP population dynamics.

Should input controls continue to be the preferred instrument for future management of either fishery, the use of catch rate reference points that relate exploitable biomass to MSY or MEY may be appropriate. Given the potential variation in WKP population size between and within seasons, the monitoring of fishery catches against MSY and MEY reference points can provide fishery managers and industry feedback on the stock status and help to ensure that economic returns are optimised and the level of harvest is appropriate to the exploitable biomass. This approach emphasises the importance of accurate catch monitoring, so it is encouraging that the SGWCPFA is currently investigating the development of an electronic logbook for the SGPF. By monitoring catch rates against reference points, the fishery can account for the highs and lows of recruitment, and greater focus can be directed on management strategies rather than the uncertainty associated with MSY or MEY estimates. O'Neill *et al.* (2014) simulated catch rate reference points for the EKP fishery and found favourable performance of catch rate indicators, but only when a meaningful upper limit was placed on total fleet effort.

6.4 Data limitations and future research

The analyses presented in this study are the most comprehensive attempt thus far to evaluate the WKP population and economic status of the GSVPF and SGPF through the development of the first bio-economic model for these fisheries. Although the best available data were used, the uncertainties of some model inputs are noted here.

The estimated spawner-recruitment parameters were fundamental for determining stock status, and the assessments assumed that standardised catch rates were proportional to abundance. Unfortunately, vessel-specific data were not available prior to 1991, which precluded standardisation of those catches. Consequently, there appeared to be little contrast, with consistent time series of harvests and effort since 1991, particularly for the SGPF. A lack of contrast in fisheries data can be problematic in that, although fisheries management is rarely treated as an experiment, it is difficult to fully understand without observation how recruitment would respond over a broad range of spawning stock sizes (Walters and Martell, 2004).

Despite a lack of contrast, model estimates of biomass appeared sensible throughout the fisheries' histories, responding to the different levels of harvests in an expected manner. Nevertheless, it became apparent during analyses that the inclusion of better estimates of exploitable biomass in the model would help considerably to improve the reliability of the stock assessment and reference points. In the latest independent review of the GSVPF, Dichmont (2014) also identified the need for better estimates of biomass indices, and that consideration should be given to conducting biomass survey(s) with a stratified random design or post-stratification of existing survey data. Given that the fraction of prawns in the swept area that are actually retained in the trawl codend can have a significant influence on the biomass estimate, the retention fraction of ~0.5 for WKP from Joll and Penn (1990) may also require investigation.

Although most model parameters are based on the results of auxiliary studies or by fitting the model to the available data, there are assumptions to which key model outputs are sensitive. One of the assumed parameters for the model was instantaneous natural mortality (M). We used the estimate of 0.102 month^{-1} (1.22 year^{-1}) and priors derived from WKP tag-recapture data in the GSV (Xiao and McShane, 2000a). This is quite low compared to other penaeid prawns, which tend to have mortality rates in the order of 2.4 ± 0.3 year^{-1} (García, 1988). Future assessments may benefit from sensitivity analysis of this parameter to examine the effect of varying mortality around these values.

Profit outcomes of the model are conditional on the economic data. Due to confidentiality reasons, we were unable to interrogate economic data to verify the accuracy of the supplied means by EconSearch or determine the variances. We therefore had to estimate a coefficient of variation for fixed and variable costs so that reasonable estimates of uncertainty are passed through to the model outputs. In a presentation of the model and preliminary results to industry representatives, some licence holders questioned the accuracy of some of the economic data. For example, the cost of labour as a proportion of the catch value was thought to be too high at ~0.40. To address such concerns over the representativeness of the economic data, it is essential that future economic surveys include questions tailored to the requirements for the bio-economic model, and licence holders provide accurate information and authorisation for the use of the data. We also note simulations by Punt *et al.* (2010) included projected annual fuel costs per litre, whereas in our study the cost of fuel was constant.

As part of the ongoing development of the bio-economic model, it may be useful to periodically compare outputs with those of a delay-difference model, which offers advantages in terms of simplified population mathematics and easier testing of key data uncertainties (Schnute, 1985; Quinn and Deriso, 1999). The Deriso-Schnute delay-difference model has been used in the past to assess the Torres Strait tiger prawn fishery (O'Neill and Turnbull, 2006) and the NPF (Dichmont *et al.*, 2001) and, more recently, as a comparison to the more complex length-spatial model for assessment of the EKP fishery (Courtney *et al.*, 2014). We anticipate that it would be relatively straightforward to develop a delay-difference model for comparison with the bio-economic model. Alternatively, it may be suitable to run bio-economic model simulations in the absence of a stock-recruitment relationship (given its flat nature). If these simulations were to produce similar outcomes, this would increase the confidence in recommendations for future management of the WKP resource based on modelling.

7 Benefits and adoption

The main beneficiaries of the study are the licence holders in the GSVPF and SGPF, the fish processors involved in the marketing of WKP, and fisheries managers at PIRSA Fisheries and Aquaculture.

The WKP bio-economic model developed in this project was used to calculate, for both fisheries, catch rate reference points for MSY and MEY for the first time. Subject to further development of the bio-economic model (see Section 8), these reference points have direct applicability to the GSVPF and SGPF if management continues to adopt the respective harvest strategy frameworks based on catch rates. The project also evaluated 10 management procedures for the GSVPF and 14 management procedures for the SGPF that were developed in consultation with the fisheries manager from PIRSA and industry representatives of the SVGPBOA and SGWCPFA. These management procedures reflect discussions with these stakeholder groups over the past few years, and included reductions in the number of vessels, increases in effort, changes in the pre-Christmas catch cap, spatial and/or temporal closures, and quota. A range of performance measures relating to industry functioning, current performance indicators, projected future population status and economics were used to evaluate each procedure. Analyses of management procedure simulations indicated that, in addition to a June closure and increase in pre-Christmas catch cap for the SGPF, a reduction in the number of vessels generally resulted in good overall performance in both fisheries (although financing the removal of vessels was not included in the simulations).

Preliminary results were presented to GSVPF licence holders and the management committee of the SGWCPFA on 9 September 2014. Adoption of the main findings pertaining to MSY, MEY or management procedures are contingent on further development of the model, ongoing dialogue between PIRSA Fisheries and Aquaculture, SARDI and industry, and understanding, acceptance and commitment by all stakeholders. The model has been acknowledged in the new management plan for the SGPF as a potential motive for initiating a review of the recently-updated harvest strategy (PIRSA, 2014). To increase the likelihood of adoption in the SGPF, PIRSA, SARDI and industry have recently agreed on a stock assessment development program over the next few years, in which the bio-economic model will comprise one of the tools available to assist with the program. For the GSVPF, a new management plan is currently under development; it is expected that a similar path (to the SGPF) will be facilitated to move the fishery closer to adopting the model.

Whilst the developed model will greatly improve the assessment of the GSVPF and SGPF with respect to evaluating biological and economic performance, it does not tell the fisheries managers and industry how the fisheries should be managed. Rather, subject to further development, the bio-economic model should be viewed as a tool that is designed to provide information about the current status of the WKP stocks relative to their biological reference points, and how the stocks might respond to specific management actions.

8 Further development

This study is a first for WKP and, as such, is a pilot for further development. Therefore, advice to industry and managers should be appropriate to and acknowledge any limitations of the model. As the modelling of population dynamics and economics is complex, care will also be taken to ensure that this advice is disseminated in a language that can be understood.

Future work should include sensitivity analyses of key parameters. For example, the estimated stock steepness parameter was relatively high compared to other penaeid stocks and, while slower growth in a cooler climate may be a plausible explanation, it is important to understand the effect of varying this parameter on model outputs. Also, we assumed instantaneous natural mortality for WKP in SG to be the same as the estimate derived from tag-recapture studies in GSV. Sensitivity analysis of this parameter would indicate whether it is appropriate to use the same estimate for both stocks.

Standardised catch rates are clearly one of the important inputs for the model. There was some lack of contrast in the 1991—2013 data, and under these circumstances, model outputs tend to be less certain. Further analyses may be worthwhile to explore the possibility of including pre-1991 catch rates, as they may provide the contrast required for a more accurate representation of abundance and fishing mortality. The inclusion of other variables for better quantification of fishing power would also improve the standardisation of catch rates. In the meantime, if model estimates are to be used for management, it would be prudent for decision-makers to err on the conservative side with respect to confidence intervals provided with these estimates.

As noted in the methods, the current behaviour and variance in the size-transition matrices (Figure F.7; Appendix Figure G.7) may limit simultaneous model fits to the size composition and standardised catch rate data. Further exploratory work is required to compare a simpler gamma approach (Haddon, 2001), build the current growth model into the stock model, and assess the use of a two-stage model to estimate growth by modelling the probability of moulting, together with a distribution for the moult increment. The latter could be gamma-distributed and would not depend on the length of the prawn. The probability of moulting would depend on length (with larger prawns moulting less often) and be chosen to make the mean growth increment (including the zeroes) match the postulated growth curve. Application of the latter idea will depend on the distributional form of the tag-recapture data.

MEY is sensitive to changes in fishing costs and fish prices; however it is not feasible to update the model and adjust MEY with respect to short-term fluctuations in factors affecting MEY (Australian Government, 2007). Whilst 3-5 years is appropriate for most fish stocks, a 2-year timeframe may be more appropriate for short-lived species such as WKP. The harvest strategies for the GSVPF and SGPF would therefore need to be flexible in this regard. In the interim, some of the data limitations (e.g. concerns with the economic data) and future research (e.g. compare outputs with those of a delay-difference model) outlined in Section 6.4 could be addressed.

9 Planned outcomes

The project outputs have contributed directly to the planned outcomes. A major advance in the quantitative stock assessment capabilities for the GSVPF and SGPF is now available with the WKP bio-economic model. For the first time, model-derived reference points for MSY and MEY were estimated and management procedures were evaluated. Although further development of a newly-developed model is inevitable, the results presented can be considered real-life examples of how the model can contribute towards greater profitability for these fisheries.

10 Conclusion

Objective 1. Collate and analyse available data for the Gulf St Vincent and Spencer Gulf prawn fisheries for integration into the bio-economic model.

This objective has been met. The development of the WKP bio-economic model would not have been possible without consolidating much of the information and data on the GSVP and SGPF that has been generated over many years of research conducted to support management of these fisheries. Further analyses were done for each fishery to standardise commercial and survey catch rates, estimate exploitable biomass, identify probability of recruitment by length and generate monthly size-transition matrices for male and female prawns. All model inputs were formatted in Excel.

Objective 2. Modify the existing Eastern King Prawn bio-economic model to fit the Gulf St Vincent and Spencer Gulf prawn fisheries data.

This objective has been met. The model for WKP was adapted from the EKP model and developed in Matlab with the input data from Objective 1. During the fitting process, we encountered different model solutions from the size composition data versus the standardised catch rates. To address this problem, the maximum likelihood estimation process was conducted in two stages: firstly, to estimate selectivity and recruitment pattern parameters; and secondly, to fix these parameters in a second optimisation tuned primarily to catch rate data. This two stage approach was undesirable and further work beyond this project is required to achieve simultaneous model fits to both the size composition and standardised catch rate data.

Objective 3. Determine economically optimal fishing strategies for the Gulf St Vincent and Spencer Gulf prawn fisheries.

This objective has been met. A key output of the model is the evaluation of management strategies. A range of management procedures were developed in consultation with industry and the fisheries manager, and these included reductions in the number of vessels, increases in effort, changes in the pre-Christmas catch cap, spatial and/or temporal closures, and quota. Simulations indicated that, in addition to a June closure and increase in pre-Christmas catch cap for the SGPF, a reduction in the number of vessels generally resulted in good overall performance in both fisheries, whereas quota did little to improve profitability.

Objective 4. Develop an approach to incorporate optimal fishing strategies into the harvest strategy for each fishery.

This objective has been partially met. Preliminary results were presented to GSVPF licence holders and the management committee of the SGWCPFA on 9 September 2014. Further presentations are likely to be required, but this will be determined in response to needs of industry and management, as adoption of the main findings pertaining to MSY, MEY or optimal management procedures are contingent on further discussion, acceptance and commitment between all stakeholder groups. We are confident that the project's finding will influence future harvest strategy development for the GSVPF and SGPF. The model has been acknowledged in the new management plan for the SGPF as a potential motive for initiating a review of the recently-updated harvest strategy (PIRSA, 2014) and, for the GSVPF, there has been regular dialogue with PIRSA in relation to completion of this project and the impending development of the next harvest strategy.

Objective 5. Provide extension of the developed model and its outputs to stakeholders of other Australian prawn trawl fisheries.

This objective is ongoing. Following completion of the project, the model will undergo further development, regular updates with new data, and simulation of different management procedures as required. Whilst extension of the model and its outputs will continue to be provided to stakeholders of the GSVPF and SGPF, extension to stakeholders of other Australian prawn trawl fisheries will be provided by distribution of the final report to the Australian Council for Prawn Fisheries, industry associations and prawn researchers in other States. Upon further development of the model, we plan to also communicate findings to these groups by publication in a peer-reviewed journal and presentation at a relevant conference.

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Appendix A Intellectual property

This research is for the public domain. The report and any resulting scientific publications are intended for wide dissemination and promotion. All data and statistics presented comply with confidentiality arrangements. Matlab code for the bio-economic model can be made available upon request to CN.

Appendix B Staff

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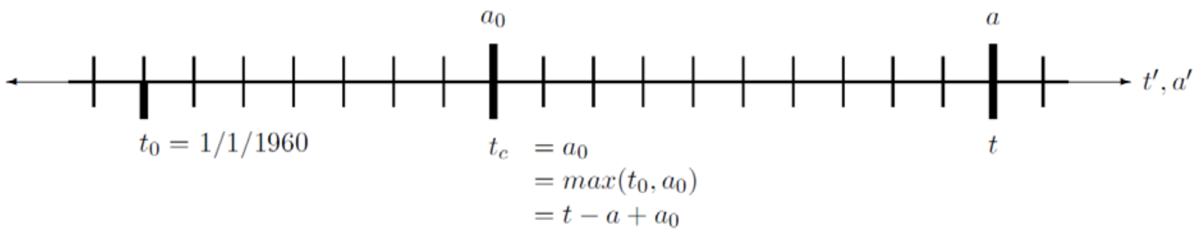
Appendix C Size transition matrix formulation

J. Carroll

C.1 Introduction

In order to generate WKP size-transition matrices we needed to determine a model of how prawns grow over time, sex, and age. We considered a seasonal von Bertalanffy growth function for tag-recapture data following the work of Xiao (Xiao, 1999; Xiao, 2000; Xiao and McShane, 2000b) combined with the growth-probabilities inspired by Chen *et al.* (2003) (Xiao and McShane, 2000b).

The simplest adaptation of Xiao's work (Xiao, 1999; Xiao, 2000; Xiao and McShane, 2000b) is if age a and time t at recapture are defined to be the same (i.e. $c = 0$ in $c = a - t$ in Xiao's formulation), then for the scenarios in which $a - a_0 < t - t_0$ (prawn is born after t_0 and grows to age a_0):



and thus the increase in size is determined by the difference between:

$$L(a,t) = \text{Length at recapture, and}$$
$$L(a_0, t - a + a_0) = \text{Length at release.}$$

C.2 Model

We consider the growth in length L in a given time period Δt to be instantaneously described by

$$L(a + \Delta a, t + \Delta t) - L(a,t) = K(a,t)\, f\left[L(a,t)\right]\Delta t, \tag{1}$$

characterised by some growth function $K(s + a - t, s) = K_0 + A\cos\left(\frac{2\pi}{T}\right)\left(s - t_\phi\right)$, for values of von Bertalanffy parameters K_0, A, T, and t_ϕ to be determined or specified. The expression Z is given by

$$Z = -K_0(a - a_0) - \frac{AT}{\pi}\sin\left(\frac{\pi}{T}\right)(a - a_0)\cos\left(\frac{2\pi}{T}\right)\left[t - t_\phi - \frac{1}{2}(a - a_0)\right]. \tag{2}$$

This is an adaptation of a von Bertalanffy model for seasonal growth function. Assuming that the growth is a simple function of lengths

$$f\left[L(a,t)\right] = L_{\max} - L(a,t), \tag{3}$$

the solution is easily verified to be

$$L(a,t) = L_{\max} - \left[L_{\max} - L(a_0, t - a + a_0)\right]\exp(Z). \tag{4}$$

C.3 Data and processing

Prawn tag-recapture studies were conducted by SARDI Aquatic Sciences in SG from Dec 1988—Nov 1996 and GSV from Oct 1984—Jun 1991. Summary statistics for recaptured prawns before and after processing are detailed in Table C.1 for GSV and Table C.2 for SG. Processing of data involved the removal of animals that had not been at liberty for at least 30 days, as well as those that indicated anomalously large negative growths (carapace length reduced by 2 mm or more). Animals with small positive or negative growth were likely to be attributed to measurement error but not with any rigorous or symmetric procedure, so these remained in the data.

Table C.1. Summary statistics for tag-recaptured WKP in the GSVPF. L refers to carapace length (mm).

Statistic	L at release	L at recapture	ΔL	Days at liberty
MALES				
Original data (n = 354)				
Range	25.5-48.2	26.7-49.5	-4.1-17.7	2-1111
Mean	37.4	39.9	2.5	108
Processed data (n = 323)				
Range	25.5-48.2	30.5-49.5	-0.5-17.7	30-1111
Mean	37.6	40.3	2.7	117
FEMALES				
Original data (n = 170)				
Range	24.4-61.0	28.7-61.7	-4.7-28.2	13-1115
Mean	42.7	46.8	4.1	120
Processed data (n = 148)				
Range	24.4-61.0	33.6-61.7	-0.6-28.2	30-1115
Mean	42.9	47.6	4.7	134

Table C.2. Summary statistics for tag-recaptured WKP in the SGPF. L refers to carapace length (mm).

Statistic	L at release	L at recapture	ΔL	Days at liberty
MALES				
Original data (n = 2545)				
Range	21.1-49.6	22.4-50.6	-10.1-20.4	0-1320
Mean	34.9	37.8	2.9	104
Processed data (n = 2027)				
Range	21.1-47.9	27.5-50.6	-1.5-20.4	30-1320
Mean	34.5	38.1	3.6	126
FEMALES				
Original data (n = 2019)				
Range	21.8-56.3	26.8-60.5	-11.5-26.8	0-729
Mean	38.9	42.8	3.9	107
Processed data (n = 1535)				
Range	21.8-56.3	28.4-60.5	-1.6-26.8	30-729
Mean	38.4	43.5	5.1	135

The growth per day was calculated as the simple ratio of $\delta L/D$ for change in length δL and days at liberty D. The data on growth per day indicated that once a prawn had been at liberty for at least a year, the growth resolved to an average (as one would expect if the growth rate is periodic over one year). The prawns with ages of at least several years were expected to determine the average of the periodic function well.

C.4 Fitting age to length

We can calculate the age-length curves iteratively by assuming (for the sake of mathematics) an initial (birth) length of 1 mm, then compounding each infinitesimal growth by day, since

$$L(a+\Delta a,t+\Delta t)=L(a,t)+K(a,t)f\left[L(a,t)\right]\Delta t. \tag{5}$$

In this scenario, we use Δt = 1 day and treat the formula iteratively. We find that the model is not highly sensitive to the initial length used in the iterative procedure.

C.5 Derivation of the growth function

Given the instantaneous growth function

$$K(a,t) = K_0 + A\cos\left[\left(\frac{2\pi}{T}\right)(t - t_\phi)\right], \quad (6)$$

we wish to solve Eq. (5). We can Taylor expand this, assuming that da/dt = 1 and we obtain the partial differential equation

$$\frac{\partial L(a,t)}{\partial a} + \frac{\partial L(a,t)}{t} = K(a,t)\, f\left[L(a,t)\right]. \quad (7)$$

We then wish to solve

$$\frac{\partial L(a,t)}{\partial a} + \frac{\partial L(a,t)}{t} = K(a,t)\left[L_{\max} - L(a,t)\right], \quad (8)$$

the solution for which requires constraining an arbitrary value which we can fix by specifying the initial length as $L(a_0, t - a + a_0)$. Inserting this value, we obtain

$$L(a,t) = L_{\max} - \left[L_{\max} - L(a_0, t - a + a_0)\right]\exp(Z), \quad (9)$$

where Z reduces to

$$Z = \frac{-2\pi K_0(a - a_0) - AT\sin\left[2\pi(t - t_\phi)/T\right] + AT\sin\left[2\pi(-a + a_0 + t - t_\phi)/T\right]}{2\pi}. \quad (10)$$

Using the identity

$$\sin(\theta) \pm \sin(\phi) = 2\sin\left(\frac{\theta \pm \phi}{2}\right)\cos\left(\frac{\theta \mp \phi}{2}\right), \quad (11)$$

we can transform Z to be the same as Eq. (2).

C.6 Derivation of size transition probabilities (non-seasonal)

This derivation follows the results of Chen *et al.* (2003). Assuming a simple von Bertalanffy growth function of length at a given time-step L_t with von Bertalanffy parameters, such as:

$$L_t = L_\infty\left[1 - e^{-K(t - t_0)}\right], \quad (12)$$

the growth in a given time step (e.g. 1 month) is given by:

$$\begin{aligned} \Delta L = L_{t+1} - L_t &= L_\infty\left[1 - e^{-K(t - t_0 + 1)}\right] - L_\infty\left[1 - e^{-K(t - t_0)}\right] \\ &= L_\infty - L_\infty e^{-K} e^{-K(t - t_0)} - L_\infty + L_\infty e^{-K(t - t_0)}. \end{aligned} \quad (13)$$

Eq. (12) can be rearranged to give $L_\infty - L_t = L_\infty e^{-K(t - t_0)}$ and we substitute this into the above to give

$$\Delta L = \left(L_\infty - L_t\right)\left(1 - e^{-K}\right). \tag{14}$$

Using the fit values $\overline{L_\infty}$ and $\overline{K}$ as estimates of the actual parameters, the probability of growth from length L' to length bin L is given by

$$P_{L' \to L} = \int_{\min(L)}^{\max(L)} f\left[x \middle| \overline{\Delta L_\infty}, \mathrm{Var}\left(\Delta L_\infty\right)\right] dx. \tag{15}$$

The mean $\overline{L_\infty}$ is defined as simply Eq. (14) with estimates inserted.

$$\overline{\Delta L} = \left(\overline{L_\infty} - L_t\right)\left(1 - e^{-\overline{K}}\right). \tag{16}$$

If we assume that the estimates approximate the true values such that

$$L_\infty = \overline{L_\infty} + \Delta L_\infty,\ K = \overline{K} + \Delta K, \tag{17}$$

where the errors are normally distributed as $\Delta L_\infty \in \mathrm{norm}\left(0, \sigma^2_{L_\infty}\right)$, $\Delta K \in \mathrm{norm}\left(0, \sigma^2_K\right)$, then we can write Eq. (14) (utilising the Taylor expansion of $e^{\Delta x} \sim 1 + \Delta x$) as

$$\begin{aligned} \Delta L &= \left(L_\infty - L_t\right)\left(1 - e^{-\overline{K}}\right) \\ &= \overline{\Delta L} + \left[\Delta L_\infty \left(1 - e^{-\overline{K}}\right)\right] - \left(\overline{L_\infty} - L_t\right)\Delta K e^{-\overline{K}} - \Delta L_\infty \Delta K e^{-\overline{K}} \\ &= \overline{\Delta L} + \varepsilon. \end{aligned} \tag{18}$$

We wish to find the variance of ΔL, which comprises several terms. We require the identity

$$\mathrm{Var}\left(\sum_{i=1}^{n} a_i X_i\right) = \sum_{i=1}^{n} a_i^2 \mathrm{Var}\left(X_i\right) + 2 \sum_{\{i,j\};\, i<j} a_i a_j \mathrm{Cov}\left(X_i, X_j\right). \tag{19}$$

In Eq. (18), $\overline{\Delta L}$ is simply a number, and thus has no variance. The remaining terms we consider via the identity above;

$$a_1 = \left(1 - e^{-\overline{K}}\right),\quad X_1 = \Delta L_\infty,\quad \mathrm{Var}\left(X_1\right) = \sigma^2_{L_\infty} \tag{20}$$

$$a_2 = -\left(\overline{L_\infty} - L_t\right)e^{-\overline{K}},\quad X_2 = \Delta K,\quad \mathrm{Var}\left(X_2\right) = \sigma^2_K. \tag{21}$$

We neglect the higher order $\Delta L_\infty \Delta K$ term, and apply the identity to what remains

$$\mathrm{Var}\left(\Delta L\right) = a_1^2 \mathrm{Var}\left(X_1\right) + a_2^2 \mathrm{Var}\left(X_2\right) + 2\mathrm{Cov}\left(X_1, X_2\right) \tag{22}$$

$$\begin{aligned} &= \sigma^2_{L_\infty}\left(1 - e^{-\overline{K}}\right)^2 + \left(\overline{L_\infty} - L_t\right)^2 \sigma^2_K e^{-2\overline{K}} \\ &\quad -2\mathrm{Cov}\left(L_\infty, K\right)\left(1 - e^{-\overline{K}}\right)\left(\overline{L_\infty} - L\right)e^{-\overline{K}}, \end{aligned} \tag{23}$$

which is the expression found in Chen *et al.* (2003). This is now sufficient information to calculate Eq. (15) (i.e. Eq. (43)) and generate the transition probabilities, which can be used to populate a size transition matrix.

Values of $\sigma_{L\infty}$, σ_K, and Cov(L_∞,K) are calculated as part of the 'nls' fitting procedure. For simplicity, the function f is taken to be a normal distribution with mean $\overline{\Delta L_\infty}$ and variance Var(ΔL_∞), though negative growths are neglected.

C.7 Derivation of size transition probabilities (seasonal)

We wish to reproduce the previous section's calculations for a time-dependent von Bertalanffy equation. If we take Eq. (12) and allow for a seasonal variation

$$L_t = L_\infty\left[1 - e^{Z(t,t_0)}\right], \tag{24}$$

where the function $Z(t,t_0)$ is now that which was obtained in the derivation of the growth function via Mathematica®, but with the replacement $(a - a_0) \rightarrow (t - t_0)$

$$Z(t,t_0) = -K_0(t - t_0) - \frac{AT}{2\pi}\sin\left(\frac{2\pi}{T}\right)(t - t_\phi) + \frac{AT}{2\pi}\sin\left(\frac{2\pi}{T}\right)(t_0 - t_\phi). \tag{25}$$

The combination of the sin(x) + sin(y) function into a sin(x)cos(y) function is less elegant in this case, and we retain the former. In this case, the growth in one time step (e.g. 1 month) is given by

$$\begin{aligned}\Delta L = L_{t+1} - L_t = L_t = L_\infty\left[1 - e^{Z(t+1,t_0)}\right] - L_\infty\left[1 - e^{Z(t,t_0)}\right] \\ = (L_\infty - L_t) - L_\infty e^{Z(t+1,t_0)},\end{aligned} \tag{26}$$

using the replacement of the rearrangement of Eq. (24)

$$L_\infty e^{Z(t,t_0)} = L_\infty - L_t. \tag{27}$$

The exponent $Z(t + 1,t_0)$ requires careful consideration

$$Z(t+1,t_0) = -K_0(t - t_0 + 1) - \frac{AT}{2\pi}\sin\left(\frac{2\pi}{T}\right)(t - t_\phi + 1) + \frac{AT}{2\pi}\sin\left(\frac{2\pi}{T}\right)(t_0 - t_\phi). \tag{28}$$

We can use the identity

$$\sin(\theta + \phi) = \sin(\theta)\cos(\phi) + \cos(\theta)\sin(\phi), \tag{29}$$

to rearrange the central term in the above, such that

$$\sin\left[\frac{2\pi}{T}(t - t_\phi) + \frac{2\pi}{T}\right] = \sin\left[\frac{2\pi}{T}(t - t_\phi)\right]\cos\left(\frac{2\pi}{T}\right) + \cos\left[\frac{2\pi}{T}(t - t_\phi)\right]\sin\left(\frac{2\pi}{T}\right). \tag{30}$$

If we now Taylor expand the time-independent trigonometric functions, as

$$\cos\left(\frac{2\pi}{T}\right) \sim 1 - \frac{(2\pi/T)^2}{2!} + \ldots, \quad \sin\left(\frac{2\pi}{T}\right) \sim \frac{2\pi}{T} - \frac{(2\pi/T)^3}{3!} + \ldots, \tag{31}$$

then we find

$$\sin\left[\frac{2\pi}{T}(t - t_\phi) + \frac{2\pi}{T}\right] = \sin\left[\frac{2\pi}{T}(t - t_\phi)\right] + \cos\left[\frac{2\pi}{T}(t - t_\phi)\frac{2\pi}{T}\right] + \ldots, \tag{32}$$

and thus the exponent is simplified;

$$
\begin{aligned}
Z\left(t+1,t_0\right) &= -K\left(t-t_0\right)-\frac{AT}{2\pi}\sin\left[\frac{2\pi}{T}\left(t-t_\phi\right)\right]+\frac{AT}{2\pi}\sin\left[\frac{2\pi}{T}\left(t_0-t_\phi\right)\right] \\
&\quad -K-\frac{AT}{2\pi}\cos\left[\frac{2\pi}{T}\left(t-t_\phi\right)\frac{2\pi}{T}\right] \\
&= Z\left(t,t_0\right)-K-\frac{AT}{2\pi}\cos\left[\frac{2\pi}{T}\left(t-t_\phi\right)\frac{2\pi}{T}\right],
\end{aligned}
\tag{33}
$$

and thus

$$
e^{Z(t+1,t_0)} = e^{Z(t,t_0)}e^{-K-\frac{AT}{2\pi}\cos\left[\left(\frac{2\pi}{T}\right)^2\left(t-t_\phi\right)\right]},
\tag{34}
$$

and consequently, Eq. (26) becomes

$$
\begin{aligned}
\Delta L &= \left(L_\infty - L_t\right) - L_\infty e^{Z(t+1,t_0)} \\
&= \left(L_\infty - L_t\right) - L_\infty e^{Z(t,t_0)} e^{-K-\frac{AT}{2\pi}\cos\left[\left(\frac{2\pi}{T}\right)^2\left(t-t_\phi\right)\right]} \\
&= \left(L_\infty - L_t\right)\left\{1-e^{-K-\frac{AT}{2\pi}\cos\left[\left(\frac{2\pi}{T}\right)^2\left(t-t_\phi\right)\right]}\right\}.
\end{aligned}
\tag{35}
$$

Using the fit values, the mean change in length is simply

$$
\overline{\Delta L} = \left(\overline{L_\infty} - L_t\right)\left\{1-e^{-\overline{K}-\frac{\overline{A}T}{2\pi}\cos\left[\left(\frac{2\pi}{T}\right)^2\left(t-\overline{t_\phi}\right)\right]}\right\}.
\tag{36}
$$

If we assume that the errors in these estimates are normally distributed, as

$$
\Delta L_\infty \in \mathrm{norm}\left(0,\sigma_{L_\infty}^2\right),
\tag{37}
$$

$$
\Delta K \in \mathrm{norm}\left(0,\sigma_K^2\right),
\tag{38}
$$

$$
\Delta A \in \mathrm{norm}\left(0,\sigma_A^2\right),
\tag{39}
$$

$$
\Delta t_\phi \in \mathrm{norm}\left(0,\sigma_{t_\phi}^2\right),
\tag{40}
$$

then the expanded version of Eq. (35) becomes

$$
\Delta L = \left(\overline{L_\infty} - L_t\right).
\tag{41}
$$

C.8 Size-transition matrix

As defined in Sadovy *et al.* (2007) the size-transition matrix Ξ_{L_s',L_s} describes the approximation to the probability density function for a random individual of sex s to grow from size-class L' into size-class L over a time step, as

$$
\Xi_{L_s',L_s} = \frac{\Phi_{L_s',L_s}}{\sum_{L_s''}\Phi_{L_s',L_s''}}; \quad \Phi_{L_s',L_s} = \exp\left(-\frac{\left\{\overline{L_s} - \left[L_{\infty,s}\left(1-e^{-Ks}\right)+\overline{L_s'}e^{-Ks}\right]\right\}^2}{2\sigma_s^2}\right),
\tag{42}
$$

where $L_{\infty,s}$ and K_s are the von Bertalanffy growth parameters for prawns of sex s, $\overline{L_s}$ is the average (mid-point) of size-class L_s.

Alternatively, as per Chen *et al.* (2003) the transition matrix can be populated by probabilities

$$P_{L',s\to L,s} = \int_{\min(L_s)}^{\max(L_s)} f\left[x \middle| \overline{\Delta L_{\infty,s}}, \mathrm{Var}\left(\Delta L_{\infty,s}\right)\right] dx, \tag{43}$$

where in this case,

$$\Delta L = \left(L_\infty - L_t\right)\left(1 - e^{-K}\right). \tag{44}$$

Appendix D Running Matlab *.m files

The section below describes typical steps in WKP stock simulation modelling.

With the Matlab code you can estimate MSY/MEY and stock status, quantify uncertainty using the estimated parameter covariance matrix or MCMC posteriors, project effects of management procedures on future status and performance measures and graphically visualise results.

D.1 Load data structures

1. (Start) Select fishery and ensure *.xlsx data are complete and formatted as required.
2. (Load) Type 'sa_wkp_1_data_load' at command prompt.

D.2 Setup parameters and negative log-likelihoods

1. (Setup fixpars and estpars) Select model parameters, type 'sa_wkp_2_param_setup' at command prompt.
2. (Setup nllonoff) Select NLL's for data and parameters to estimate, type 'sa_wkp_4_nll' at prompt.

   or

   Import (load) saved model parameters (estpars, fixpars, mle, nllonoff) from *.mat file.

D.3 Run stock model ('sa_wkp_3_popdyn_model')

1. Run m-file section 'Run model with current parameter values and plot' in 'sa_wkp_optimise'. Outputs saved into structures [negll,nll,pred,r].
2. Model status with current 'estpars' can be visualised by typing 'sa_wkp_5_modelplots' at prompt.
3. If model components are changed, e.g. q_s, ensure 'sa_wkp_6_popdyn_eqmodel_msymey' and 'sa_wkp_9_mse_model' are consistent.

D.4 Fit stock model to data ('sa_wkp_optimise')

1. Run m-file section 'Fit and save maximum likelihood solution' in 'sa_wkp_optimise'. Optimisation app, with plots, can also be used here.
   a. First try single optimisation runs, then
   b. Long cycle runs (overnight or weekend, fmincon then fminsearch).
2. Run simulated annealing after using optimisers above. This will search for further ML solutions and estimate covariance matrix for MCMC; type 'mcmc_wrapper_wkp_simulated_annealing' at prompt. (long run time; 5 x nparams x 5000 sims).
3. Run MCMC after simulated annealing to quantify parameter distributions. Type 'sa_wkp_mcmc" at prompt. (long run time like above).
4. Plot ML estimated parameters to evaluate model fit by typing 'sa_wkp_5_modelplots' at prompt.
5. Evaluate MCMC parameter simulations using R 'coda' package. Use R file 'R_mcmc_diagnostic_code.R'. Save MCMC simulated parameters into *.csv file.

D.5 Reference points ('sa_wkp_6_eq_refpts')

1. (Section 1) Reference point estimation on current estpars; simple visual plot included; select monthly effort pattern and objective.
2. (Section 2) Reference point simulations for errors. Reference points simulated for different effort patterns, three objectives (MSY, MEY_{fv} and MEY_v), management costs and fishing powers.
3. (Section 3) Analyse equilibrium reference points, including empirical measures.

****

D.6 Management procedures ('sa_wkp_8_mse')

1. Simulation of management procedures (MP) can run separate to the previous steps. Section 1 of 'sa_wkp_8_mse' loads historical data ('sa_wkp_1_data_load') and management data

('sa_wkp_7_mse_data_load'), and sets data for the simulations. Near line 35, simulation parameters need to be set or loaded from m-file.

2. Now run the simulation for each MP from Section 2 of 'sa_wkp_8_mse' using m-file 'sa_wkp_9_mse_model', storing results data into structure sim.
3. Simulations will be saved according to the fishery label in MP, with a date tag.

D.7 Analyse management procedures ('sa_wkp_10_mse_analysis')

1. This m-file analyses future simulations for evaluating WKP management procedures (aka management strategy evaluation, MSE). (Section 1) First part of m-file loads the sim data from a *.mat file.
2. (Section 2) Here the sim data are reshaped for analysing each key performance measure.
3. (Section 3) Boxplots of performance measures for each MP.

Appendix E Input data summaries

E.1 Standardised commercial catch rates

The modelling of commercial catch rates in the GSVPF and SGPF was carried out on daily logbook data from fishing years 1991—2013. Older data in the fisheries could not be resolved spatially or to vessel and were therefore not standardised. Three GLM types were explored for predicting the year-month effect on commercial catches (in kg block-vessel-night^{-1}): 1) a Gaussian normal error distribution and identity link fitted to cubic-root transformed catches; 2) a Poisson distribution with log link and errors adjusted for overdispersion (called 'quasipoisson' in R); and 3) a Gaussian distribution with identity link (Figure E.1; E.5). By virtue of residuals most closely resembling a normal distribution, the cube root model was preferred for standardising catch rates in both fisheries (Figure E.4; E.8). The standardised and unstandardised model fits showed some differences, particularly for the GSVPF, but not in overall trend (Figure E.1). Effort was by far the most influential variable on standardised catches, although year-month, region, vessel, lunar phase and, for the SGPF only, cloud cover, were also highly significant (Table E.1; E.2). Overall goodness-of-fit was high, with adjusted R^2 values of 0.86 and 0.74 for GSVPF and SGPF models, respectively.

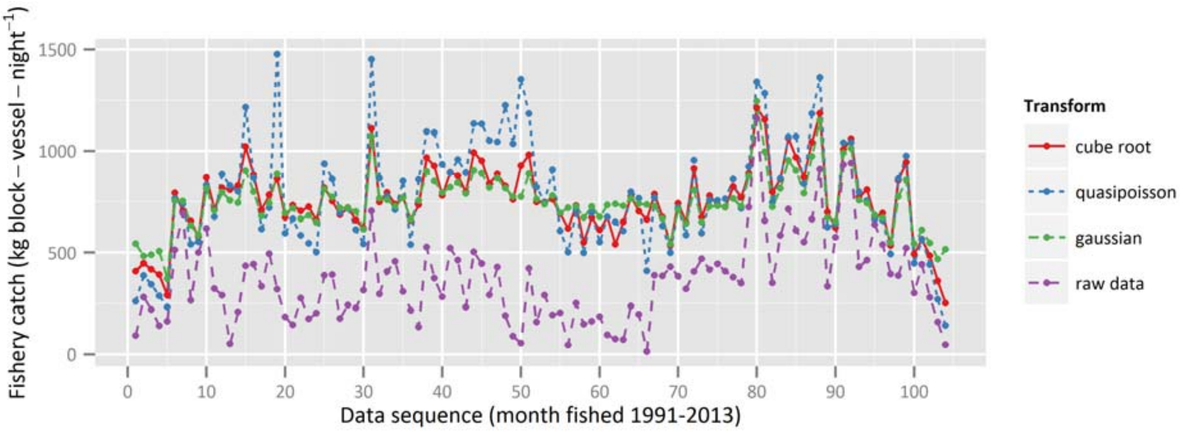


Figure E.1. Comparison of model-predicted and unstandardised (nominal reported data) mean commercial catch rates by year-month in the GSVPF. The cube root transformation was chosen for the final model, where the standardised catch by a vessel in a block per night was predicted by region, hours fished, vessel, lunar phase and cloud cover.

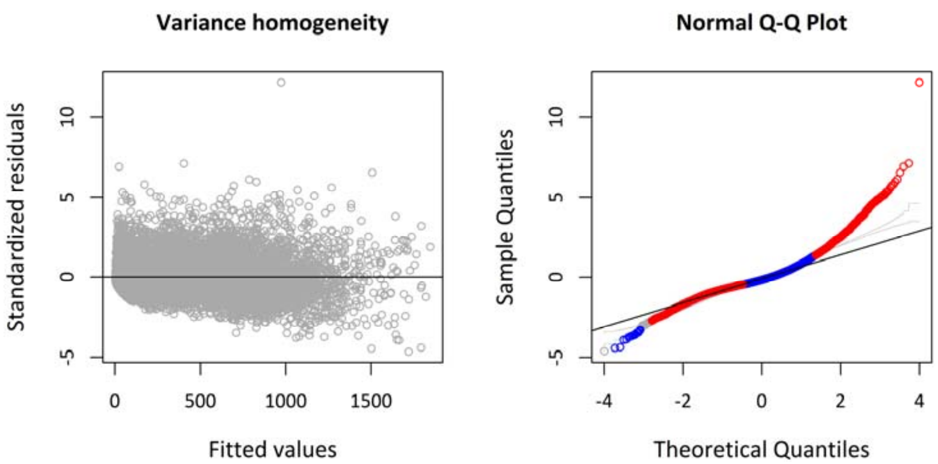


Figure E.2. Diagnostic plots of the Poisson GLM fitted to GSVPF commercial catches.

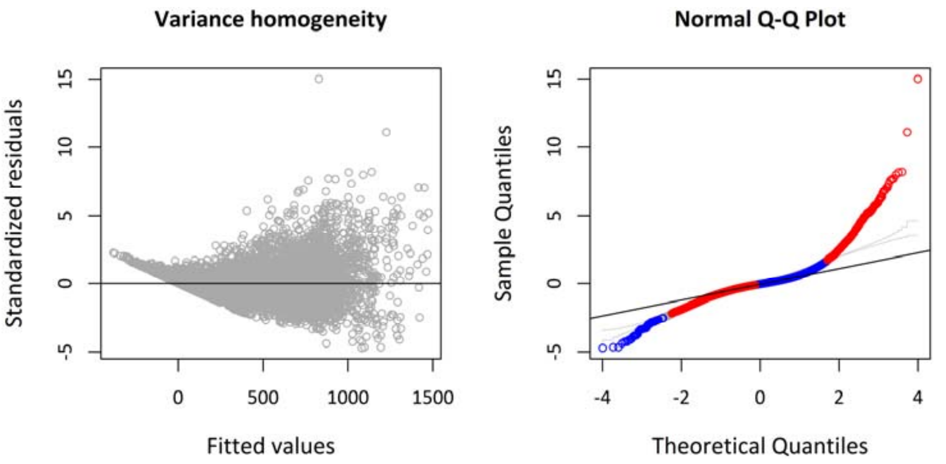


Figure E.3. Diagnostic plots of the Gaussian GLM fitted to untransformed GSVPF commercial catches.

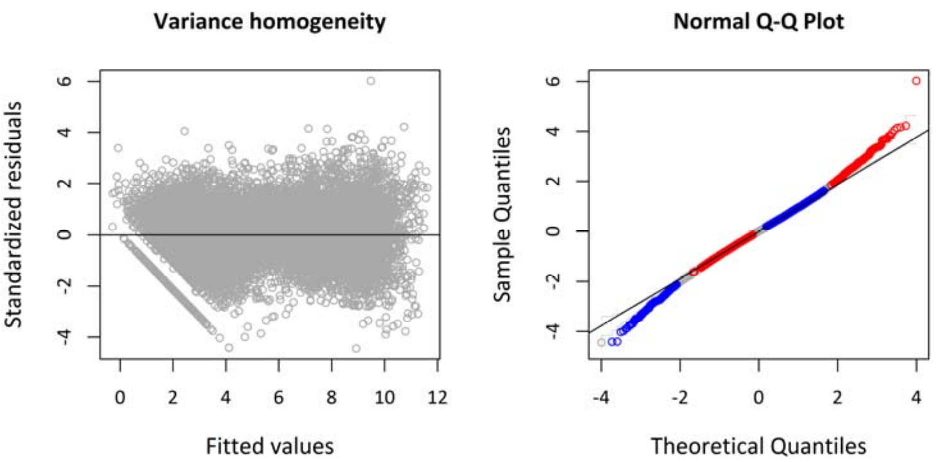


Figure E.4. Diagnostic plots of the Gaussian GLM fitted to cube-root transformed GSVPF commercial catches.

Table E.1. Analysis of deviance table for the cube root GLM used to standardise commercial catch rates in the GSVPF (R^2adj = 0.86). Abbreviations: SS, sum of squares; df, degrees of freedom; *F*, *F*-statistic; *P*, probability.

Source of variation	**SS**	**df**	***F***	***P***
Year-month	5375	103	59.7	<2.20E-16
Region	297	9	37.7	<2.20E-16
Effort (hours)$^{1/3}$	77954	1	89136.2	<2.20E-16
Vessel	158	9	20.1	<2.20E-16
Lunar phase*	44	1	50.8	1.07E-12
Lunar phase (lagged ¼ phase)	67	1	77.0	<2.20E-16
Cloud cover†	9	1	10.77	0.00104
Residuals	13158	15045		

* Fraction of the moon illuminated at midnight AEST.
† Mean fraction from three-hourly readings between 1800 and 0600 hours.

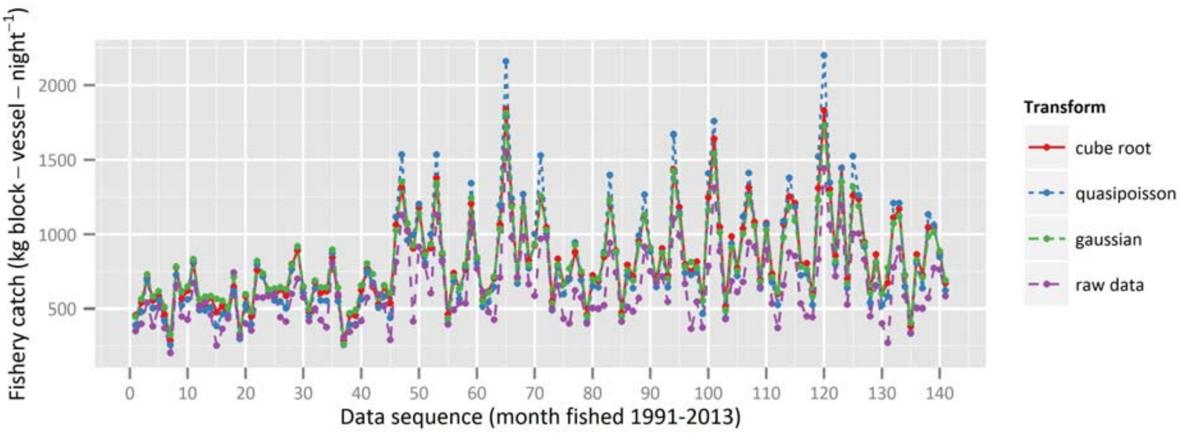


Figure E.5. Comparison of model-predicted and unstandardised (nominal reported data) mean commercial catch rates by year-month in the SGPF. The cube root transformation was chosen for the final model, where the standardised catch by a vessel in a block per night was predicted by region, hours fished, vessel and lunar phase.

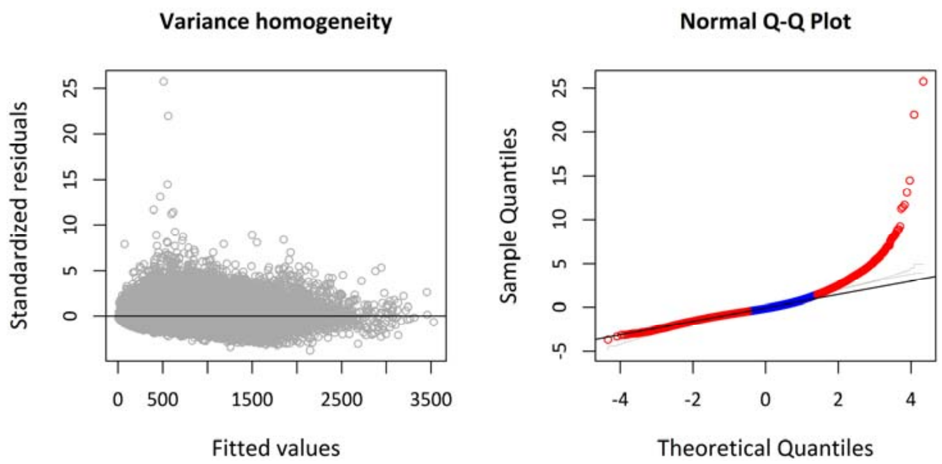


Figure E.6. Diagnostic plots of the Poisson GLM fitted to SGPF commercial catches.

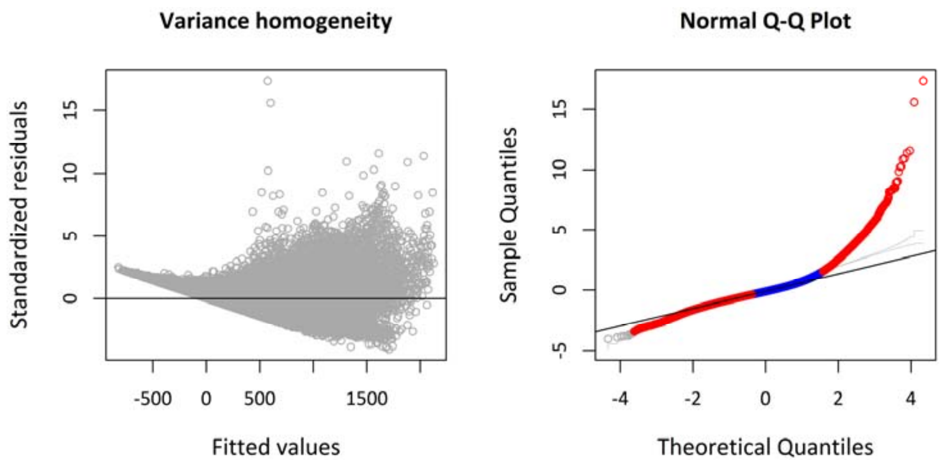


Figure E.7. Diagnostic plots of the Gaussian GLM fitted to untransformed SGPF commercial catches.

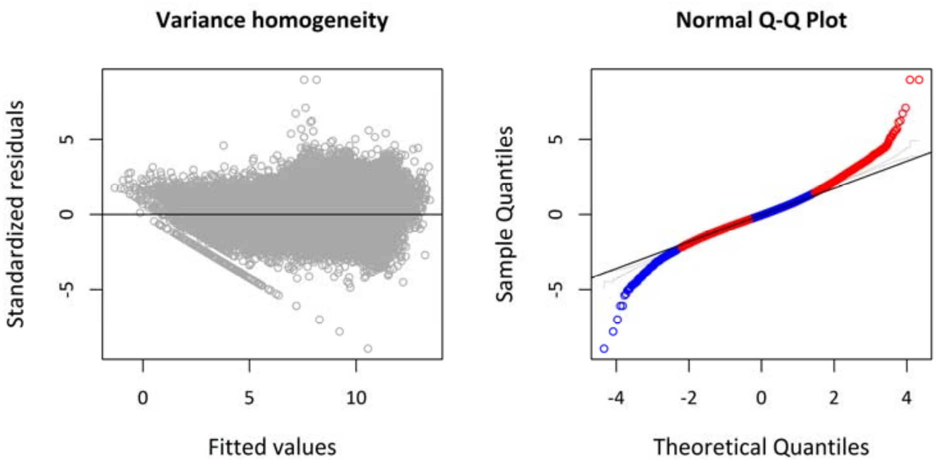


Figure E.8. Diagnostic plots of the Gaussian GLM fitted to cube-root transformed SGPF commercial catches.

Table E.2. Analysis of deviance table for the cube root GLM used to standardise commercial catch rates in the SGPF (R^2adj = 0.74). Abbreviations: SS, sum of squares; df, degrees of freedom; *F*, *F*-statistic; *P*, probability.

Source of variation	**SS**	**df**	***F***	***P***
Year-month	72870	140	371.9	<2.20E-16
Region	14759	9	1171.6	<2.20E-16
Effort (hours)$^{1/3}$	168727	1	120547.7	<2.20E-16
Vessel	2613	38	49.1	<2.20E-16
Lunar phase*	6725	1	4804.8	<2.20E-16
Lunar phase (lagged ¼ phase)	4582	1	3273.9	<2.20E-16
Residuals	95875	68498		

* Fraction of the moon illuminated at midnight AEST.

E.2 Standardised survey catch rates

The modelling of survey catch rates in the GSVPF and SGPF was carried out on surveys conducted from fishing years 2005—2013, when consistent and regular survey programs were adopted in both fisheries. The same three GLM types (as for modelling commercial catches) were explored for predicting the year-month effect on survey catches (in kg trawl-shot^{-1}) (Figure E.9; E.13). Residual plots indicated that the best model fits in both fisheries were obtained by cube root transformation of catches (Figure E.12; E.16). Year-month, region, vessel and, for the GSVPF only, tide direction were all highly significant (Table E.3; E.4); however, the low adjusted R^2 values of 0.13 and 0.34 for GSVPF and SGPF, respectively, suggest potential sources of variability are unaccounted. A review of survey designs, variables recorded and interactions are required (Dichmont, 2014).

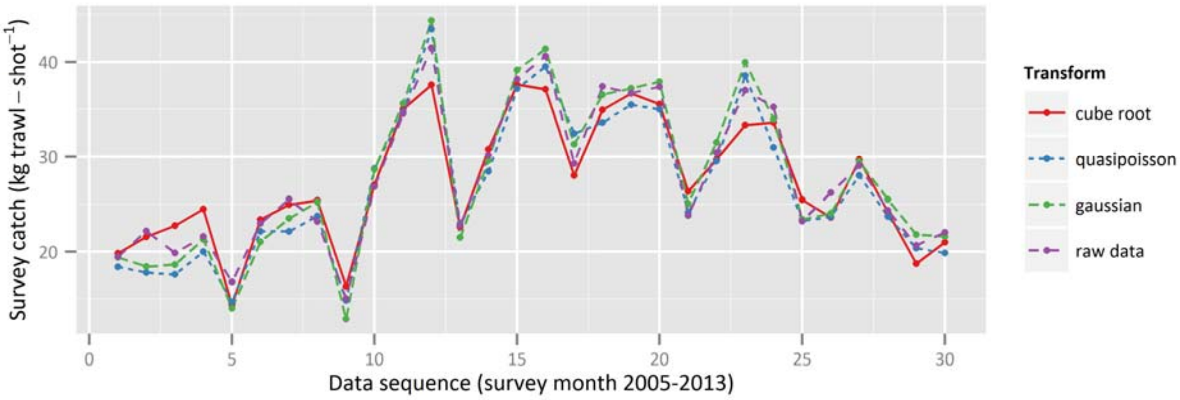


Figure E.9. Comparison of model-predicted and unstandardised (nominal reported data) mean survey catch rates by year-month in the GSVPF. The cube root transformation was chosen for the final model, where the standardised catch in a trawl shot of ~30 min duration was predicted by region and vessel.

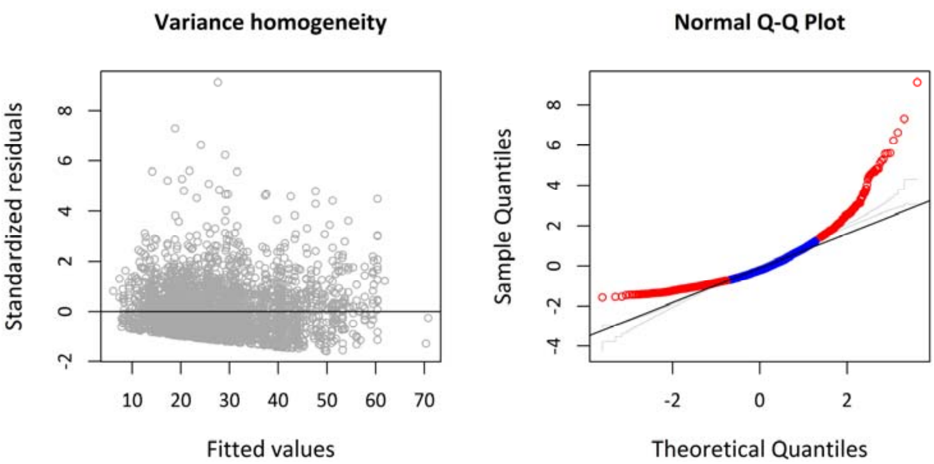


Figure E.10. Diagnostic plots of the Poisson GLM fitted to GSVPF survey catches.

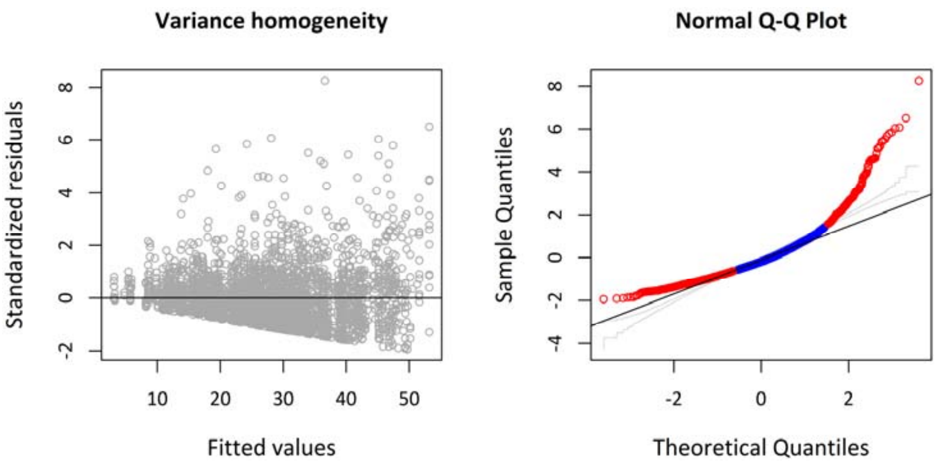


Figure E.11. Diagnostic plots of the Gaussian GLM fitted to untransformed GSVPF survey catches.

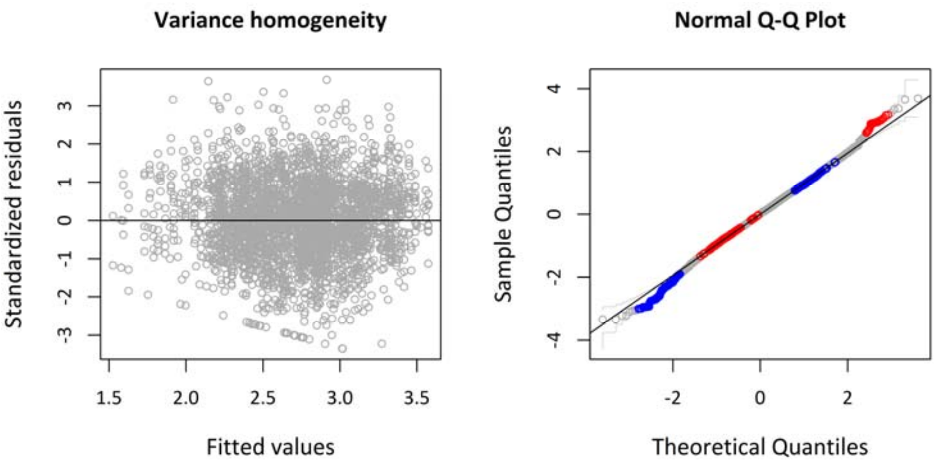


Figure E.12. Diagnostic plots of the Gaussian GLM fitted to cube-root transformed GSVPF survey catches.

Table E.3. Analysis of deviance table for the cube root GLM used to standardise survey catch rates in the GSVPF (R^2adj = 0.13). Abbreviations: SS, sum of squares; df, degrees of freedom; *F*, *F*-statistic; *P*, probability.

Source of variation	**SS**	**df**	***F***	***P***
Year-month	219.3	29	9.2	<2.20E-16
Region	133.6	7	23.2	<2.20E-16
Vessel	59.6	12	6.0	1.51E-12
Residuals	2580.0	3139		

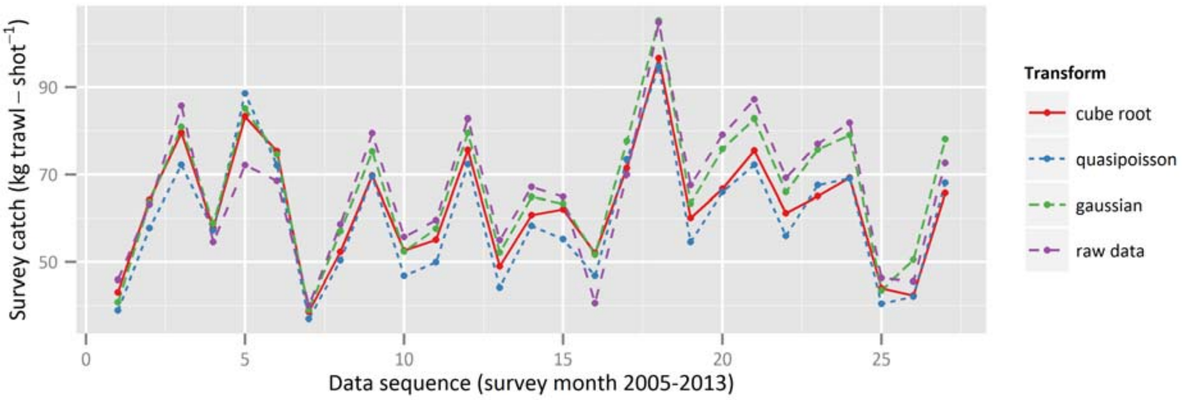


Figure E.13. Comparison of model-predicted and unstandardised (nominal reported data) mean survey catch rates by year-month in the SGPF. The cube root transformation was chosen for the final model, where the standardised catch in a trawl shot of ~30 min duration was predicted by region, vessel and tide direction.

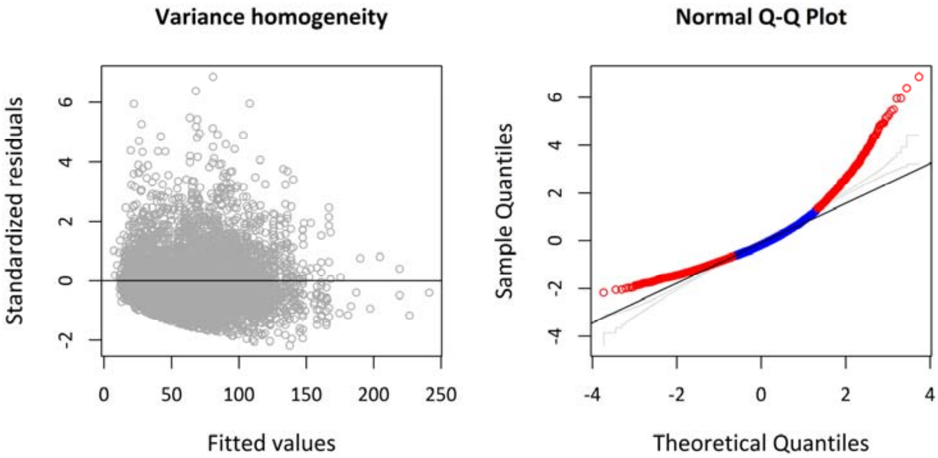


Figure E.14. Diagnostic plots of the Poisson GLM fitted to GSVPF survey catches.

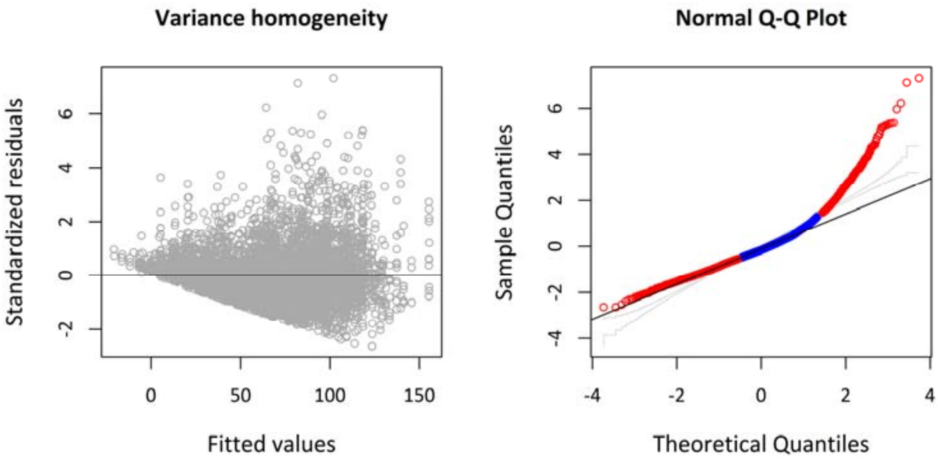


Figure E.15. Diagnostic plots of the Gaussian GLM fitted to untransformed SGPF survey catches.

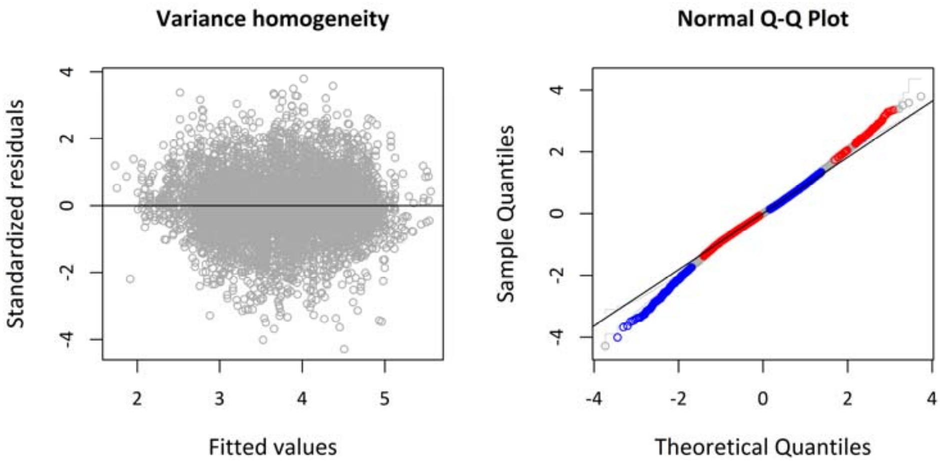


Figure E.16. Diagnostic plots of the Gaussian GLM fitted to cube-root transformed SGPF survey catches.

Table E.4. Analysis of deviance table for the cube root GLM used to standardise commercial catch rates in the SGPF (R^2adj = 0.34). Abbreviations: SS, sum of squares; df, degrees of freedom; *F*, *F*-statistic; *P*, probability.

Source of variation	**SS**	**df**	***F***	***P***
Year-month	433.6	26	21.3	<2.20E-16
Region	1537.9	8	246.0	<2.20E-16
Vessel	103.5	24	5.5	<2.20E-16
Tide direction*	65.3	3	27.9	<2.20E-16
Residuals	4080.3	5222		

* Relative to the direction of the trawl shot (i.e. AT, against tide; ST, slack tide; WT, with tide).

E.3 Size composition data

Length-frequency samples from each survey conducted in the GSVPF from 2005—2012 and SGPF from 2005—2013 demonstrated consistent size distributions by sex and survey month, with females attaining a greater size than males (Figure E.17; E.18). Samples pooled by survey month in each fishery showed a greater proportion of small prawns appearing in frequency distributions from February/March onwards (5th percentile: 25-28 mm for GSVPF; 27-28 mm for SGPF) than in November/December (5th percentile: 30-33 mm for GSVPF; 30-32 mm for SGPF) (Table E.5; E.6). This agrees with our understanding that peak recruitment generally occurs around February at 12-15 months of age (Carrick, 2003).

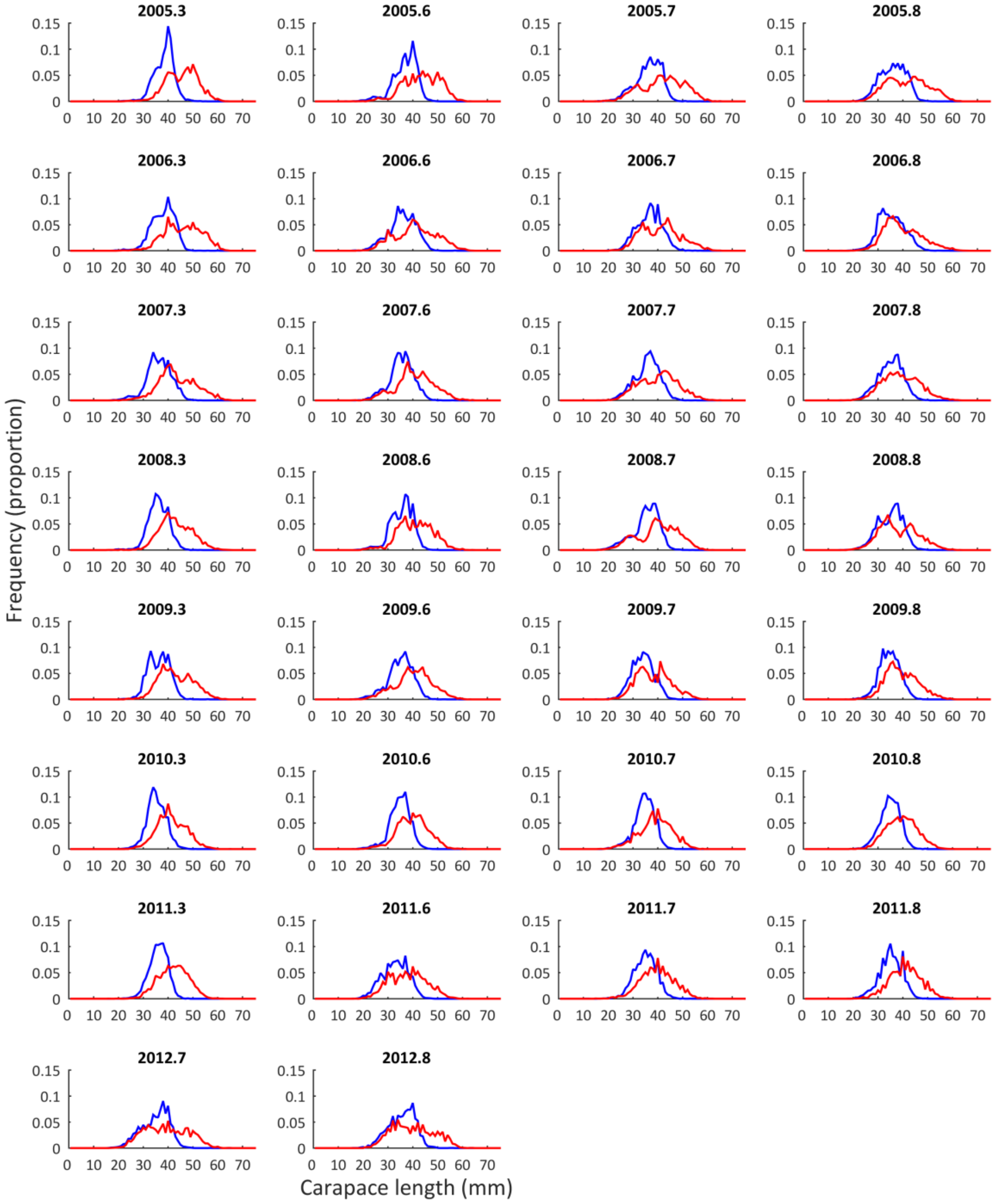


Figure E.17. Length frequencies of male (blue) and female (red) WKP collected from each survey in the GSVPF from 2005—2012. Each plot is labelled with fishing year and month.

Table E.5. Summary statistics for length-frequency samples from GSVPF pooled by survey month (fish month in parentheses) from 2005—2012.

Statistic	Carapace length (mm)			
	Dec (3)	Mar (6)	Apr (7)	May (8)
Males				
Mean	36.6	35.2	35.2	35.2
5th-95th percentile	30-43	25-42	26-42	27-43
Females				
Mean	43.5	40.7	40.0	39.7
5th-95th percentile	33-55	28-53	27-52	28-52

Table E.6. Summary statistics of length-frequency samples from SGPF pooled by survey month (fish month in parentheses) from 2005—2013.

Statistic	Carapace length (mm)		
	Nov (2)	Feb (5)	Apr (7)
Males			
Mean	36.0	34.9	34.9
5th-95th percentile	30-43	27-44	27-42
Females			
Mean	41.3	40.1	38.4
5th-95th percentile	32-52	28-55	27-51

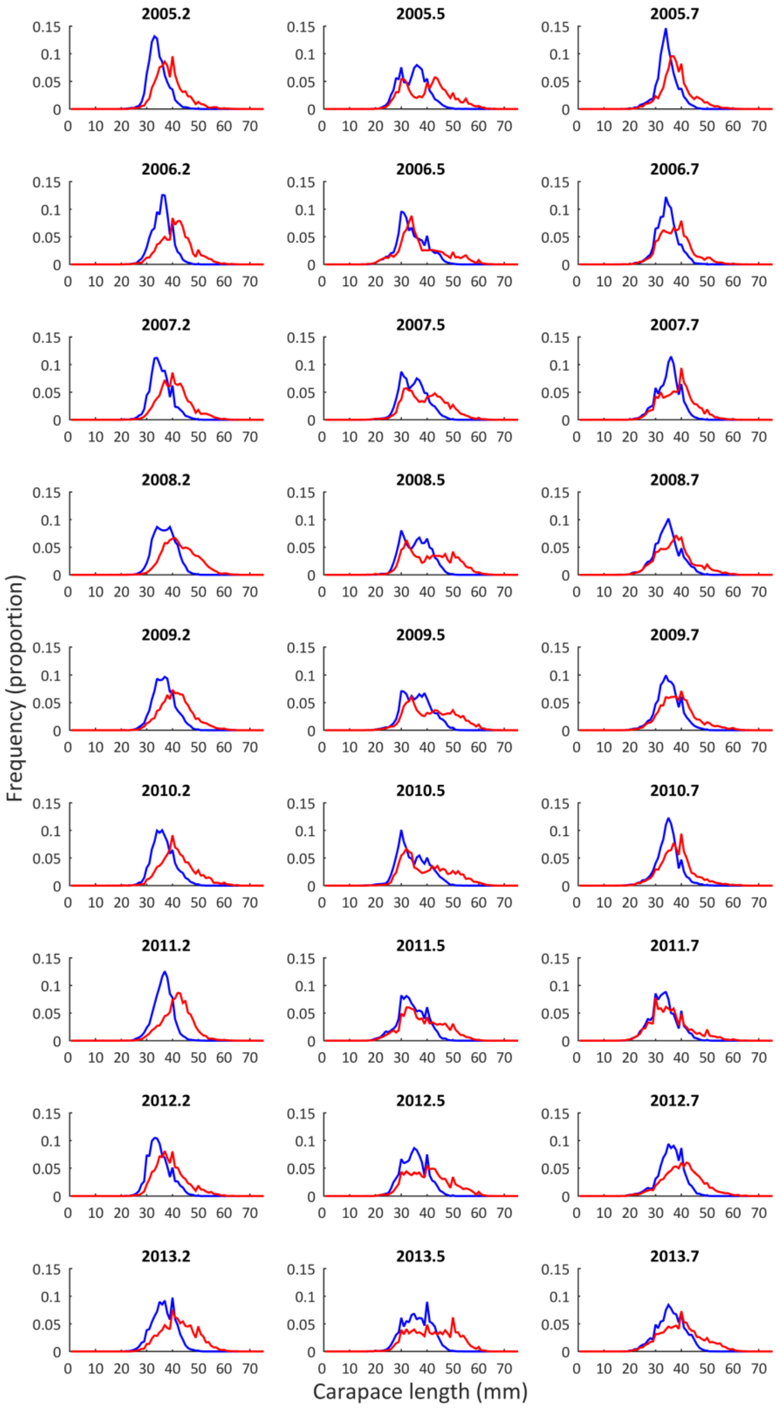


Figure E.18. Length frequencies of male (blue) and female (red) WKP collected from each survey in the SGPF from 2005—2013. Each plot is labelled with fishing year and month.

The monthly harvests by the GSVPF from 2007—2012 comprised, on average, more than one-third large prawns (10-15 lb^{-1}; 38%), more than a quarter extra-large (<10 lb^{-1}; 28%) and medium prawns (16-20 lb^{-1}; 26%), and the remainder small prawns (>20 lb^{-1}; 8%). Regression analysis indicated a significant increase in the proportion of small and medium prawns and decrease in large and extra-large prawns over this period. In the SGPF, almost half of the monthly harvests from 2003—2013 were made up of large prawns (46%), followed by medium (29%) and extra-large prawns (20%, and a small proportion of small prawns (5%). The size-grade composition in the SGPF has been relatively stable over this period, although there has been a slight but still significant increase in the proportion of medium prawns and decrease in extra-large prawns.

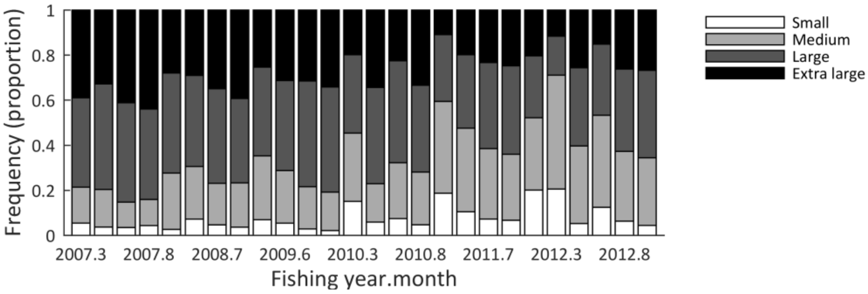


Figure E.19. Size-grade composition of monthly harvests by the GSVPF from 2007—2012.

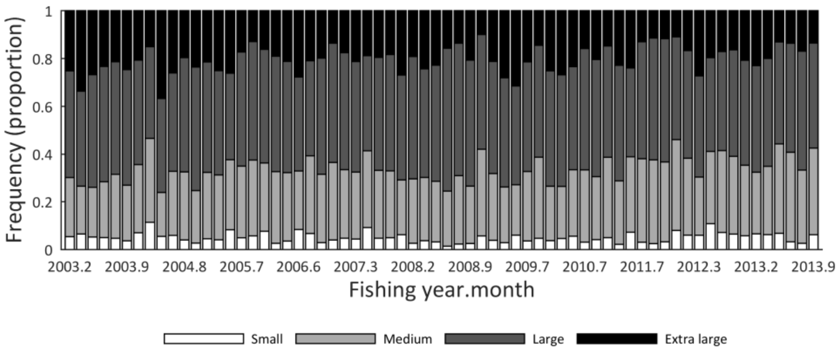


Figure E.20. Sze-grade composition of monthly harvests by the SGPF from 2003—2013.

E.4 Size-transition matrices

The size-transition matrices generated for the WKP population dynamic model are characterised by strong seasonal growth. Mean parameter values of the seasonal von Bertalanffy growth model (Eq. (6) in Appendix C) fitted to WKP tag-recapture data are summarised in Table E.7 for GSV and Table E.8 for SG, and growth trajectories are shown in Figure E.21 and Figure E.22, respectively. The derivation (from the growth model parameters) of growth rate K as a function of time predicted that males in GSV reach their maximum growth rate in mid-March, slow down to zero growth in mid-August, exhibit negative growth (shrinkage) until mid-October, then resume positive growth around mid-October for another cycle (Figure E.23). The female growth cycle occurs two weeks earlier, with maximum growth rate reached by late February and minimum growth rate approaching zero in early September. In SG, growth rates for males and females reached their maxima in early March, and were slowest in early September (Figure E.24). No growth was predicted to occur from late July to mid-October for males and from late August to late September for females. Both GSV and SG models indicated that female WKP grow almost continuously in length throughout the year but at a slower rate in certain months than males.

Table E.7. Seasonal von Bertalanffy growth parameters fitted to WKP tag-recapture data from the GSVPF.

Model	L_{max}	K_0	A	t_ϕ
Males	46.5	0.00237	0.00285	79.5
Females	61.3	0.00204	0.00171	61.4

Table E.8. Seasonal von Bertalanffy growth parameters fitted to WKP tag-recapture data from the SGPF.

Model	L_{max}	K_0	A	t_ϕ
Males	45.9	0.00243	0.00331	69.0
Females	57.1	0.00217	0.00229	72.6

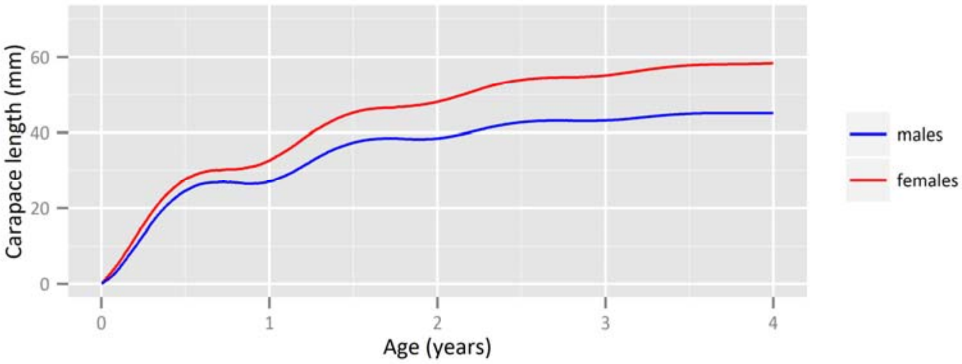


Figure E.21. Seasonal von Bertalanffy growth trajectories for male and female WKP from the GSVPF with a birth date of 1 November.

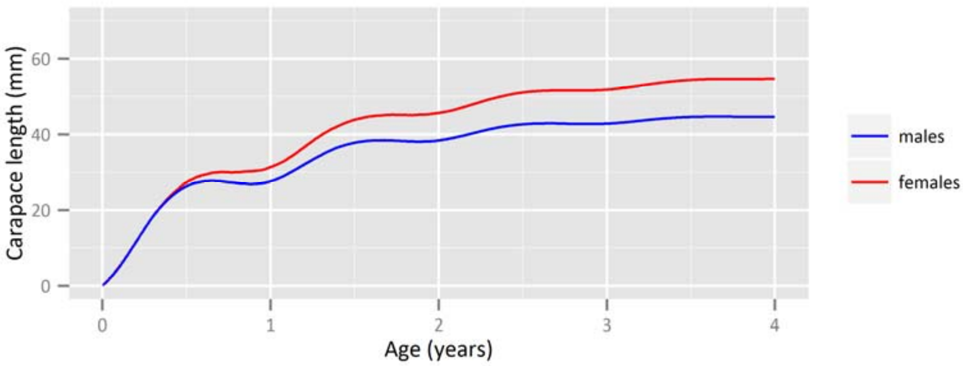


Figure E.22. Seasonal von Bertalanffy growth trajectories for male and female WKP from the SGPF with a birth date of 1 November.

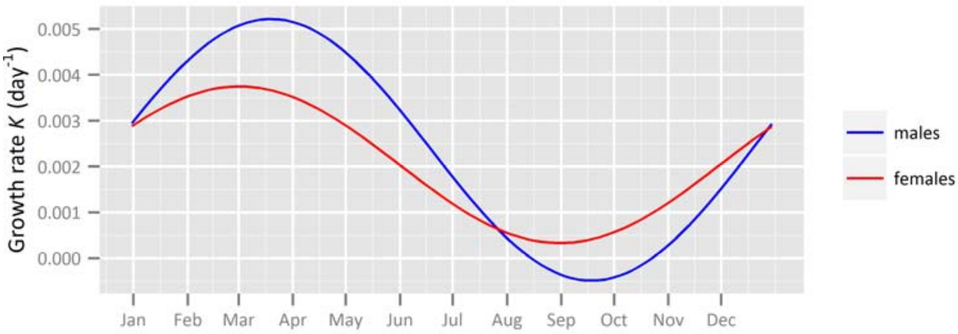


Figure E.23. Seasonal growth rate of male and female WKP from the GSVPF.

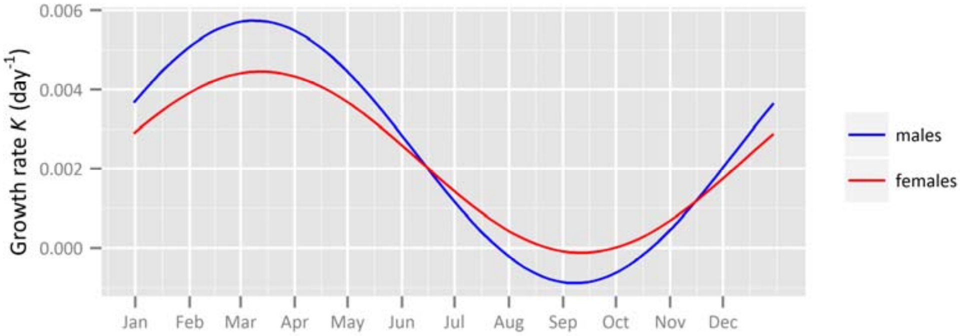


Figure E.24. Seasonal growth rate of male and female WKP from the SGPF.

E.5 Economic data

Table E.9. Breakdown of average annual vessel costs W_y in the GSVPF for 2011/12.

W_y variables	\$ vessel-year^{-1}	Proportion
Licence fee	35443	0.40
Insurance	21269	0.24
Labour (unpaid, imputed)	13723	0.15
Legal and accounting	7118	0.08
Slipping and mooring	4339	0.05
Office, administration, etc.	4307	0.05
Telephone, fax, etc.	2766	0.03
Travel and accommodation	467	0.01
Total	**89432**	

Table E.10. Breakdown of average annual vessel costs W_y in the SGPF for 2012/13.

W_y variables	\$ vessel-year^{-1}	Proportion
Licence fee	25476	0.29
Insurance	19713	0.22
Legal and accounting	10652	0.12
Slipping and mooring	5836	0.07
Labour (unpaid, imputed)	4751	0.05
Membership and association expenses	3300	0.04
Communication	3183	0.04
Boat survey	2758	0.03
Electricity	2594	0.03
Rates	2399	0.03
Repairs and maintenance (buildings)	1955	0.02
Travel and accommodation	1272	0.01
Repairs and maintenance (vehicles)	900	0.01
Rents	528	0.01
Training (other)	527	0.01
Export fees	444	0.01
Training (first aid)	110	0.00
Other	2395	0.03
Total	**88794**	

Appendix F Supplementary plots – Gulf St Vincent Prawn Fishery

F.1 Model input data

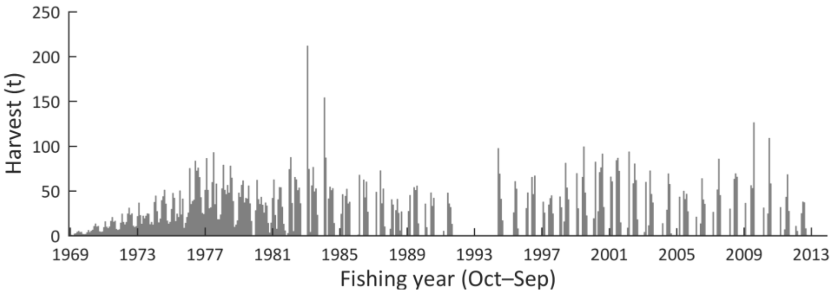


Figure F.1. Monthly harvest of WKP by the GSVPF from 1968—2012.

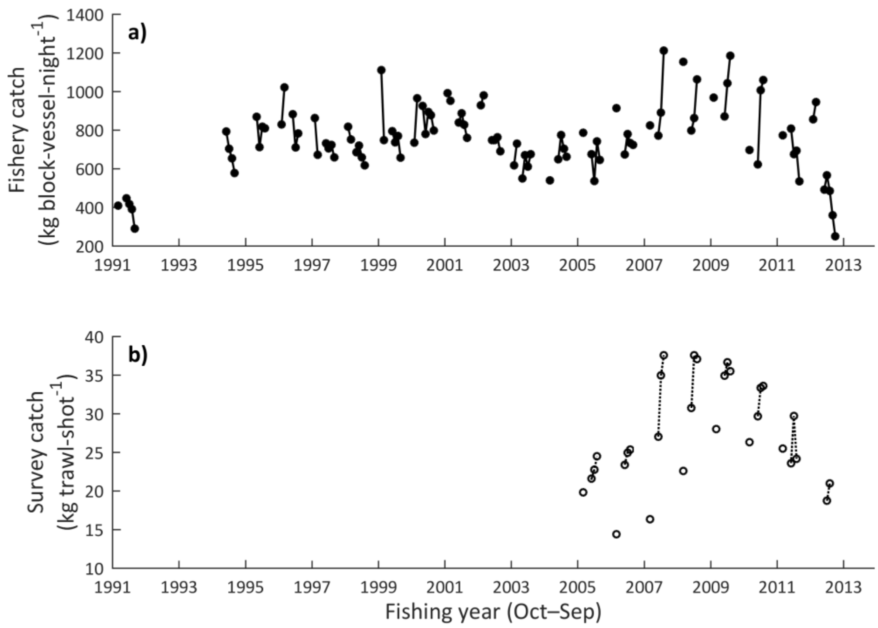


Figure F.2. Standardised mean a) fishery catches (1991—2012) and b) survey catches (2005—2012) in the GSVPF.

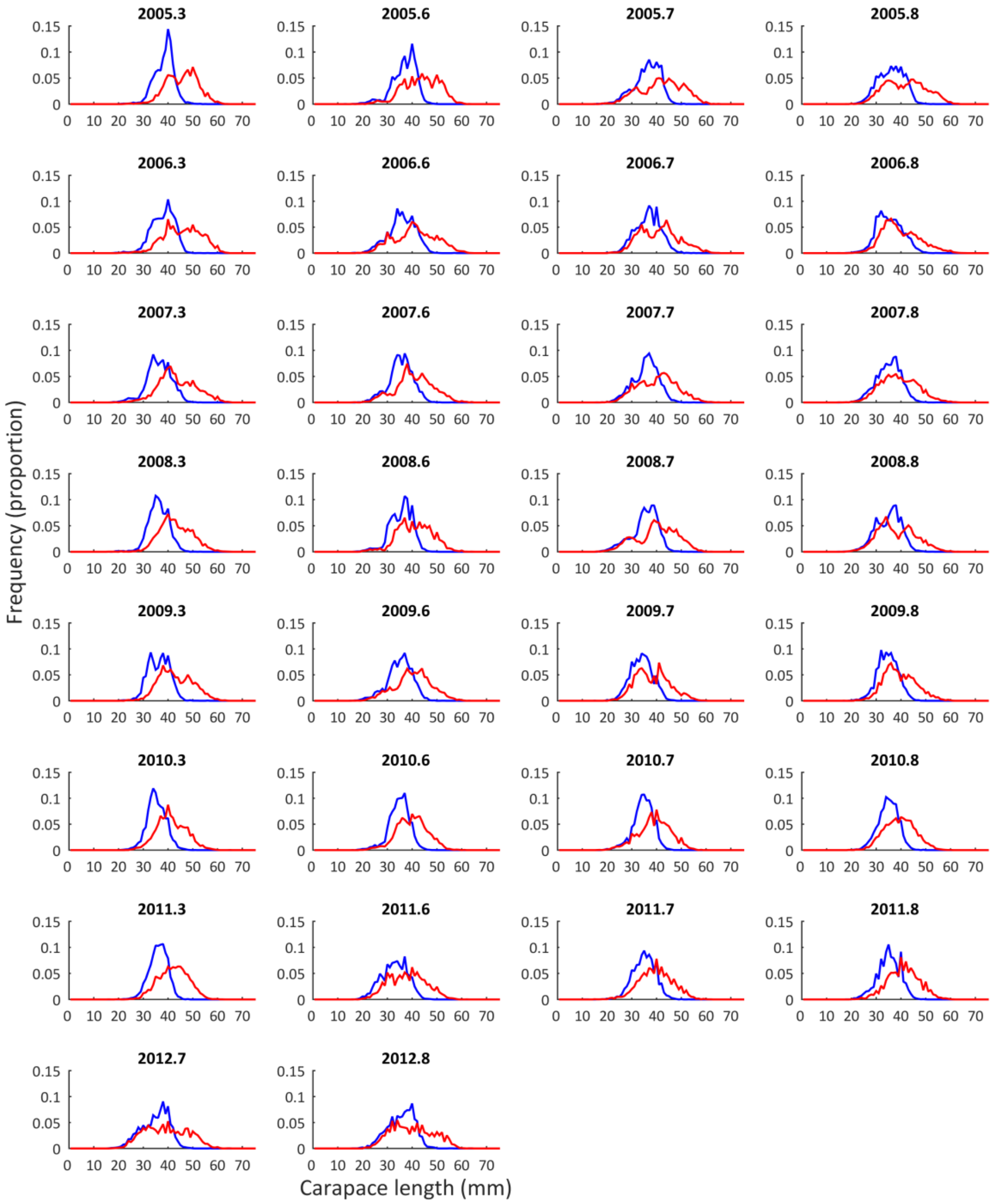


Figure F.3. Survey length-frequency distributions (proportions) for male (blue) and female (red) WKP in the GSVPF from 2005—2012. Labels refer to fishing year and month.

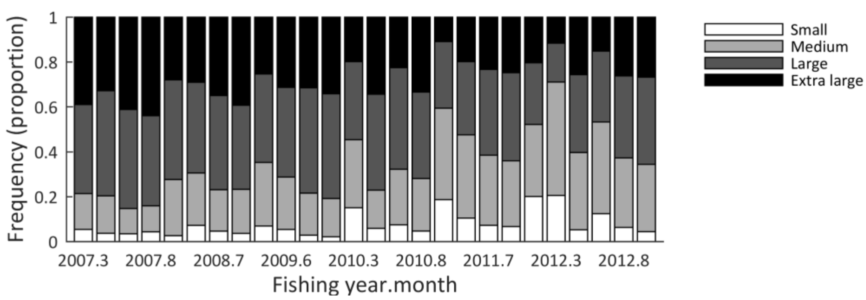


Figure F.4. Size-grade frequencies (proportions) in the GSVPF from 2007—2012.

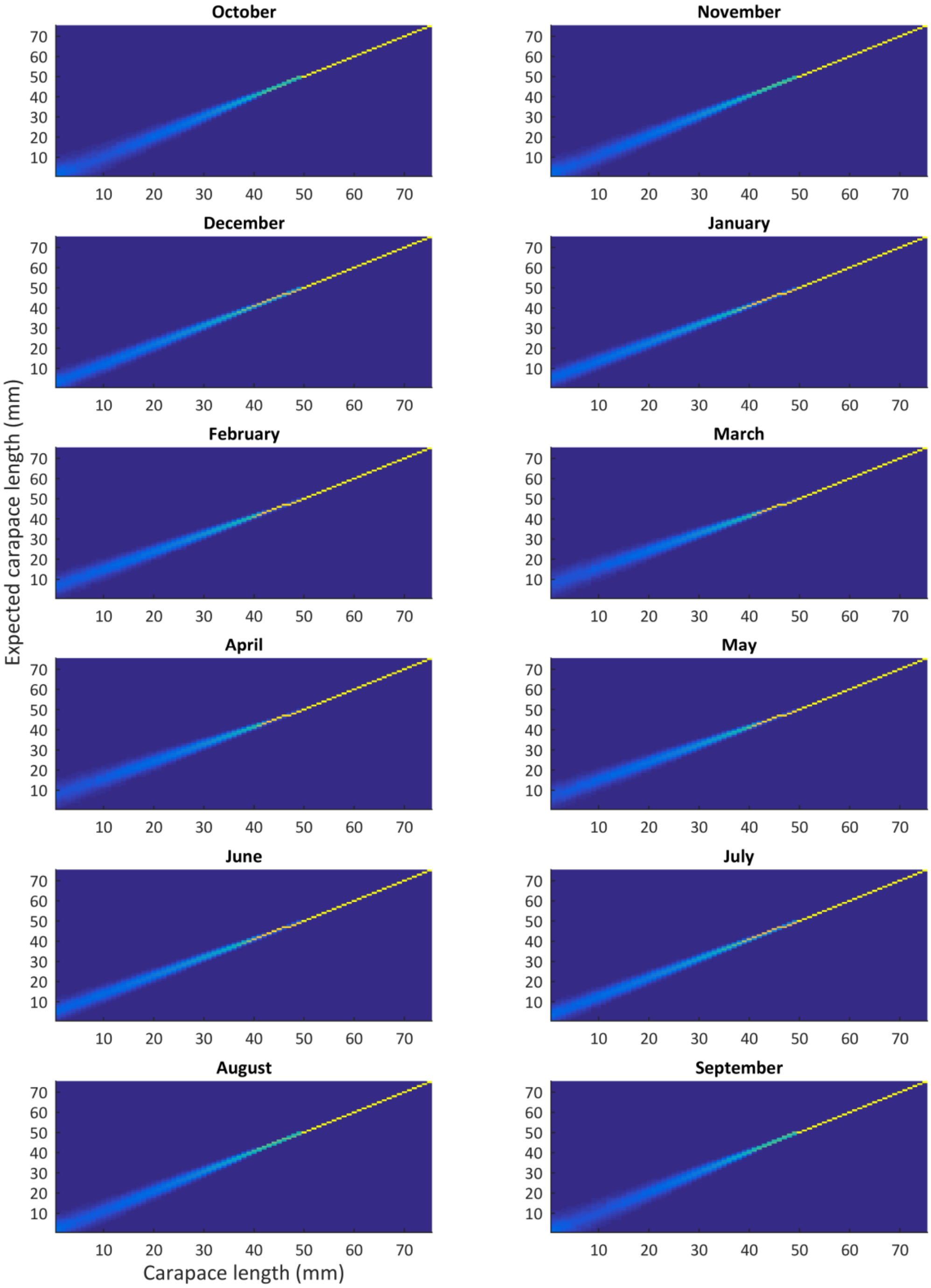


Figure F.5. Colour-scale visualisation of the size-transition matrix for male WKP in the GSVPF. The scale from blue to red indicates increasing probability of prawns of carapace length-class *l'* in the previous month growing into a new length *l* over one month.

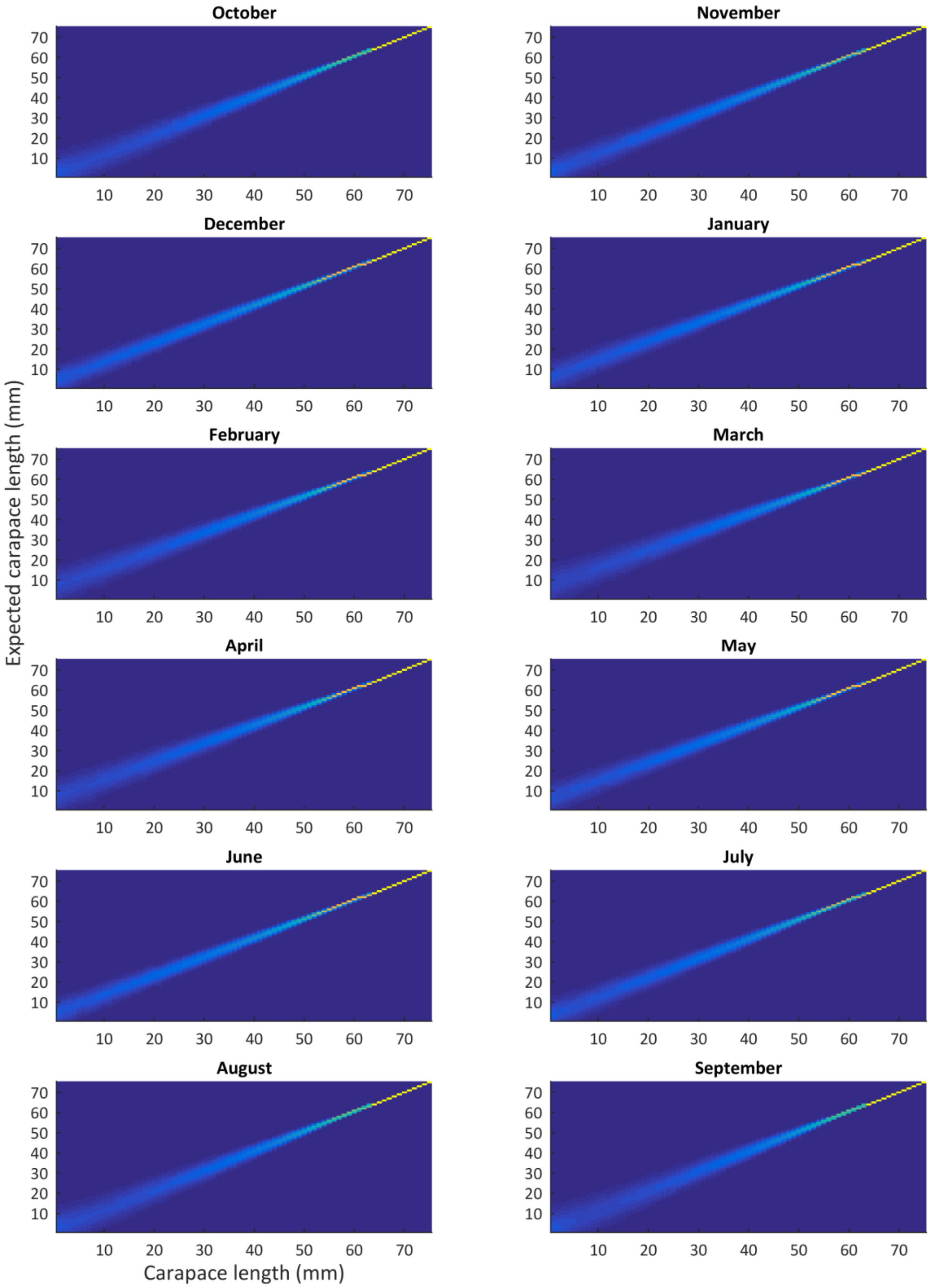


Figure F.6. Colour-scale visualisation of the size-transition matrix for female WKP in the GSVPF. The scale from blue to red indicates increasing probability of prawns of carapace length-class *l'* in the previous month growing into a new length *l* over one month.

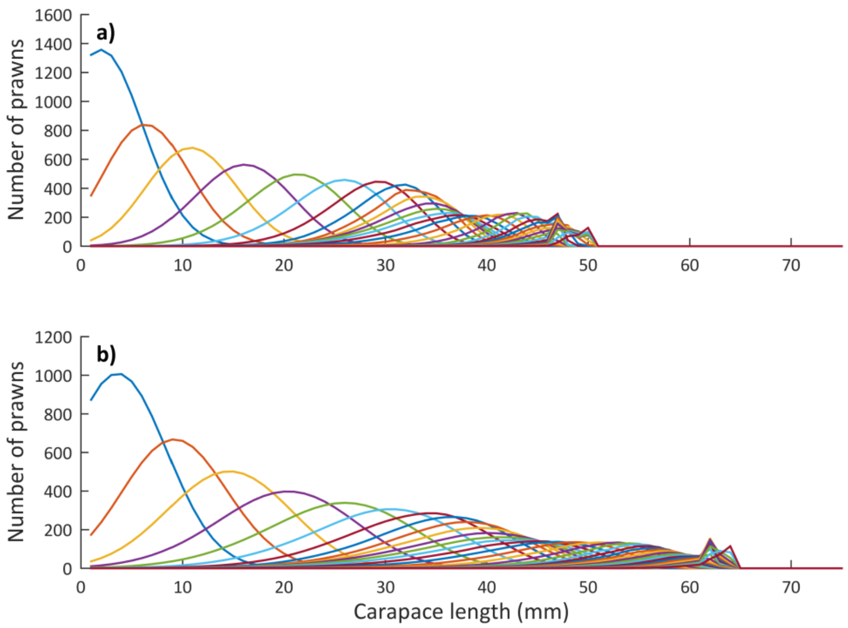


Figure F.7. Example growth of a cohort of a) male and b) female WKP in the GSVPF. Each cohort initially comprised 10000 prawns of carapace length 1 mm in October. Cohort growth was based on size-transition matrices and natural mortality, and traced for 36 months, with each successive distribution representing a month.

F.2 Model output results

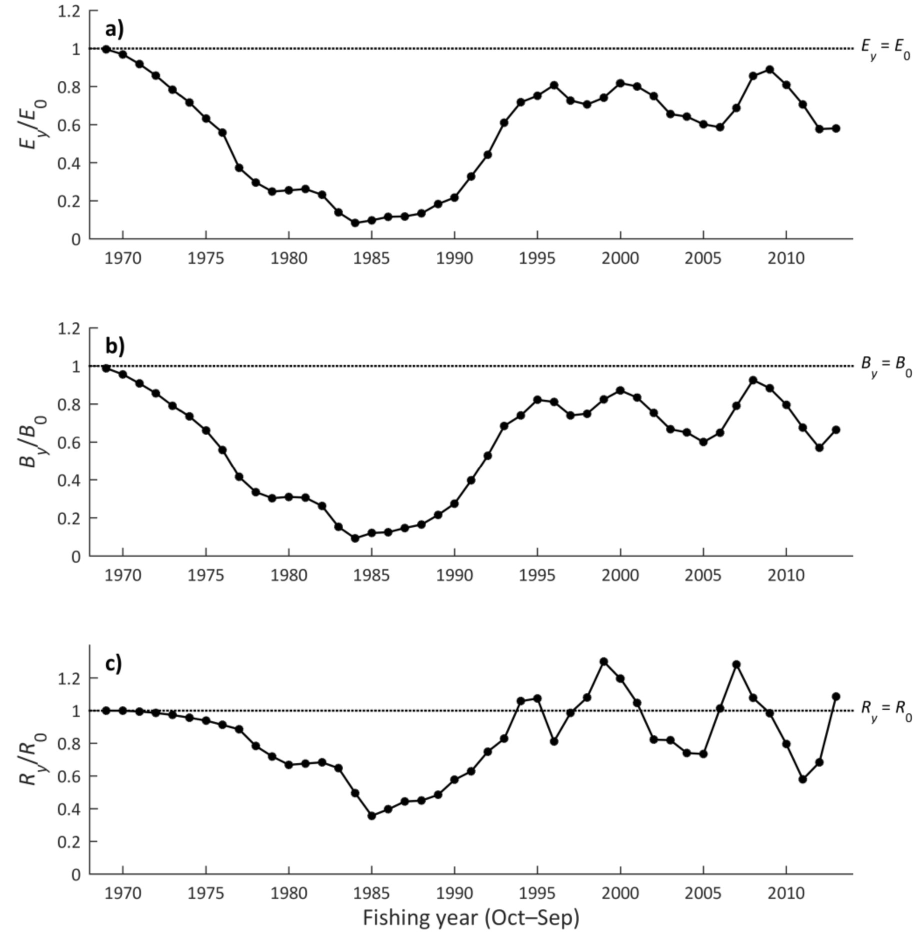


Figure F.8. WKP stock status annual plots for the GSVPF from 1991—2013: a) spawning egg production ratio (E_y/E_0); b) exploitable biomass ratio (B_y/B_0); and c) recruitment ratio (R_y/R_0). The dotted reference line indicates the estimated level of the equilibrium virgin stock (i.e. t = 0 at 1969). Deterministic recruitment was modelled from 1969—1993 and stochastic (variable) recruitment thereafter.

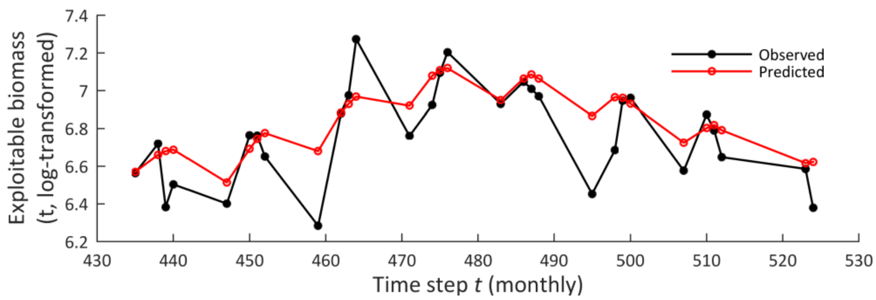


Figure F.9. Comparison of observed (survey) and predicted (model) WKP exploitable biomass by year-month in the GSVPF.

F.3 Fishery catch rate diagnostics

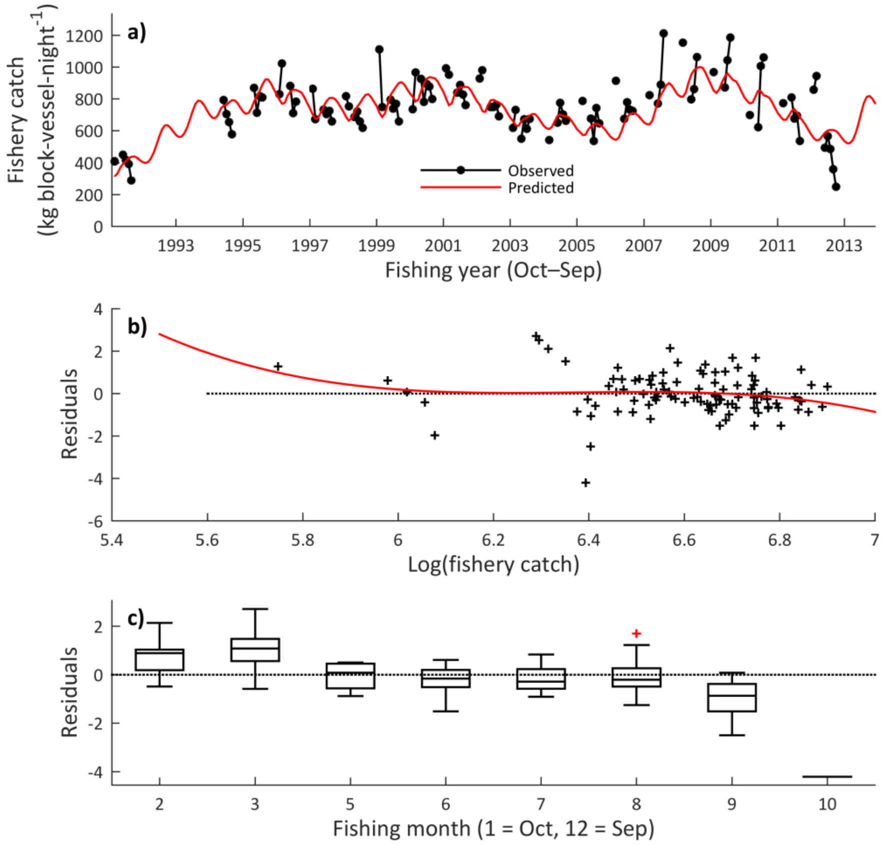


Figure F.10. Fishery catch rate fitted diagnostics for the GSVPF: a) observed (standardised) and model-predicted catch rates each month from 1991—2013; b) standardised fitted values; and c) monthly standardised residuals.

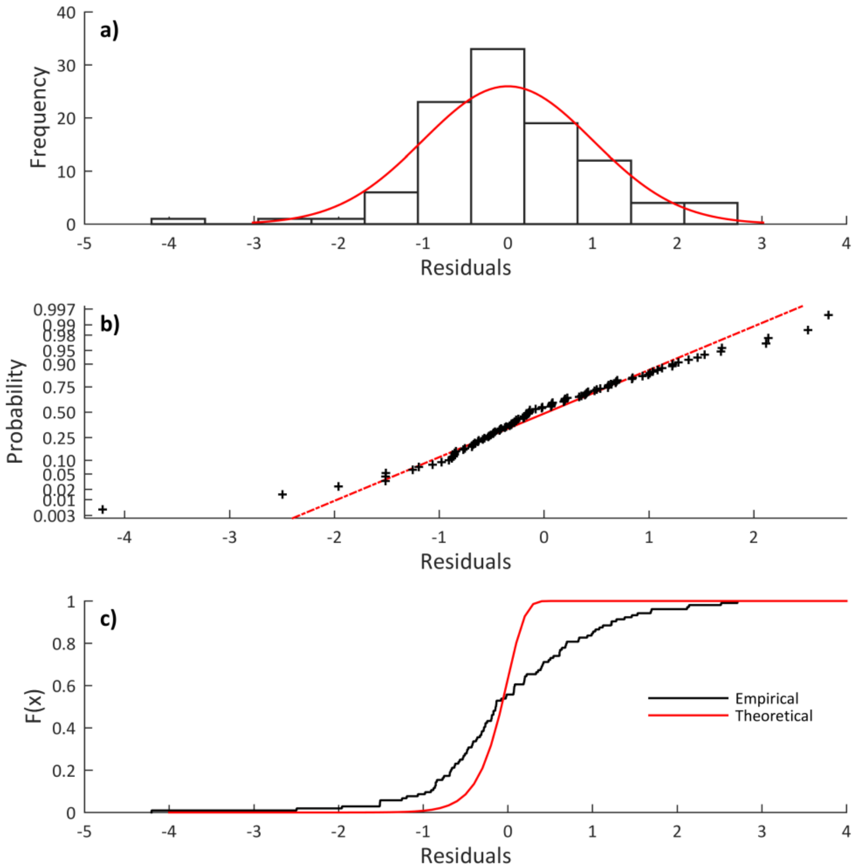


Figure F.11. Normality checks for fishery catch rates in the GSVPF: a) histogram of standardised residuals; b) probability plot of standardised residuals; and c) cumulative density function of standardised residuals.

F.4 Survey catch rate diagnostics

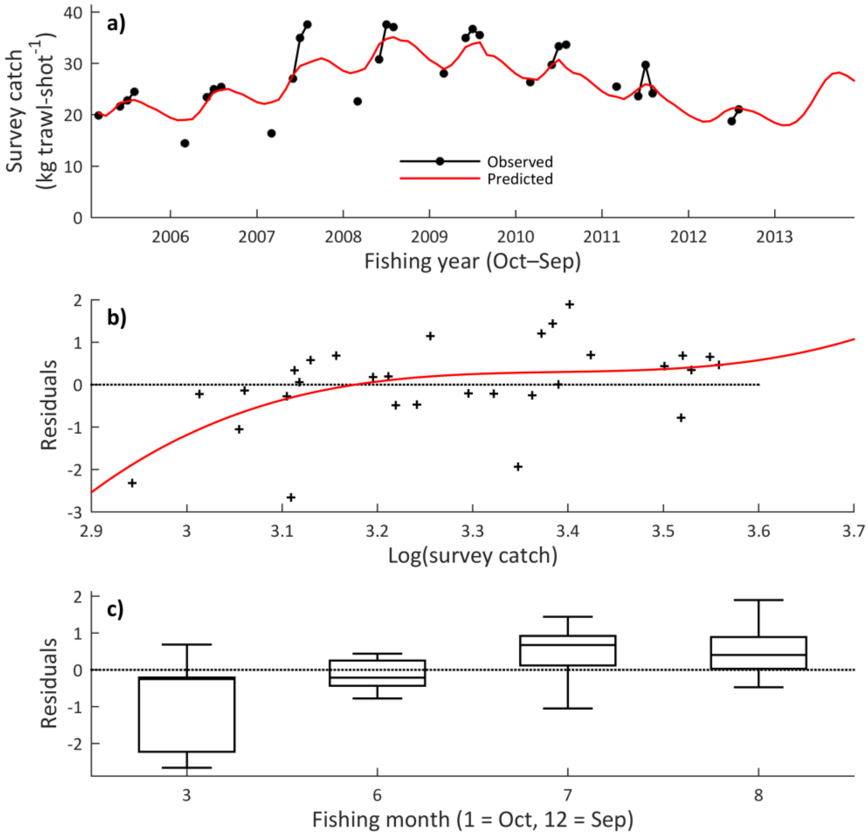


Figure F.12. Survey catch rate fitted diagnostics for the GSVPF: a) observed (standardised) and model-predicted catch rates each month from 2005—2013; b) standardised fitted values; and c) monthly standardised residuals.

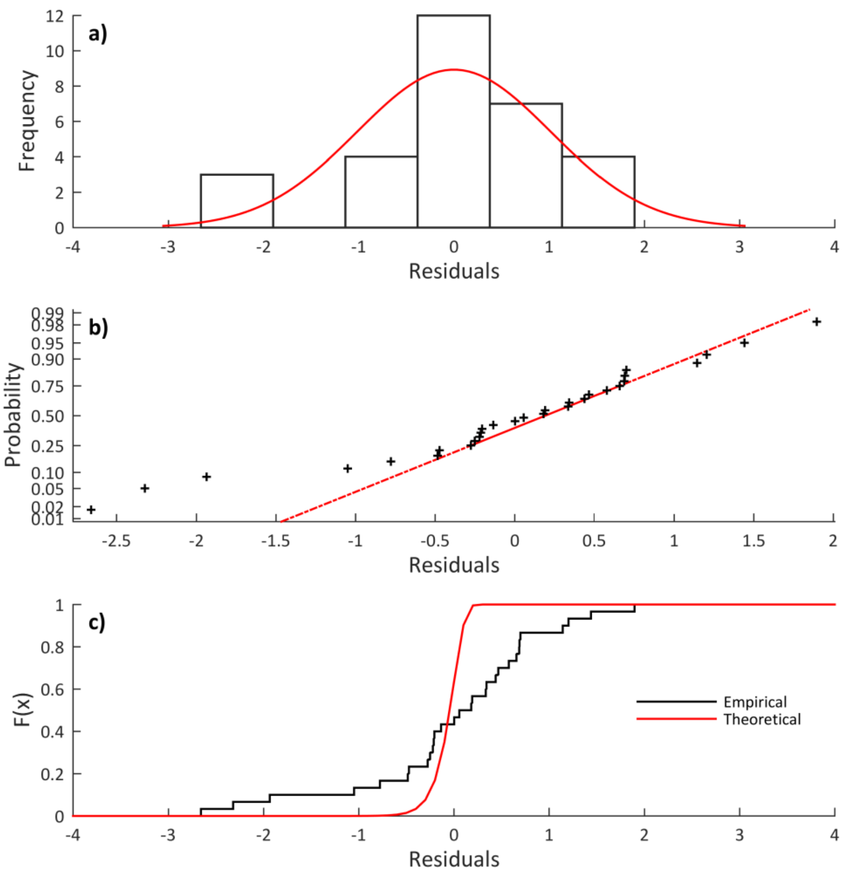


Figure F.13. Normality checks for survey catch rates in the GSVPF: a) histogram of standardised residuals; b) probability plot of standardised residuals; and c) cumulative density function of standardised residuals.

F.5 Size-grade frequency diagnostics

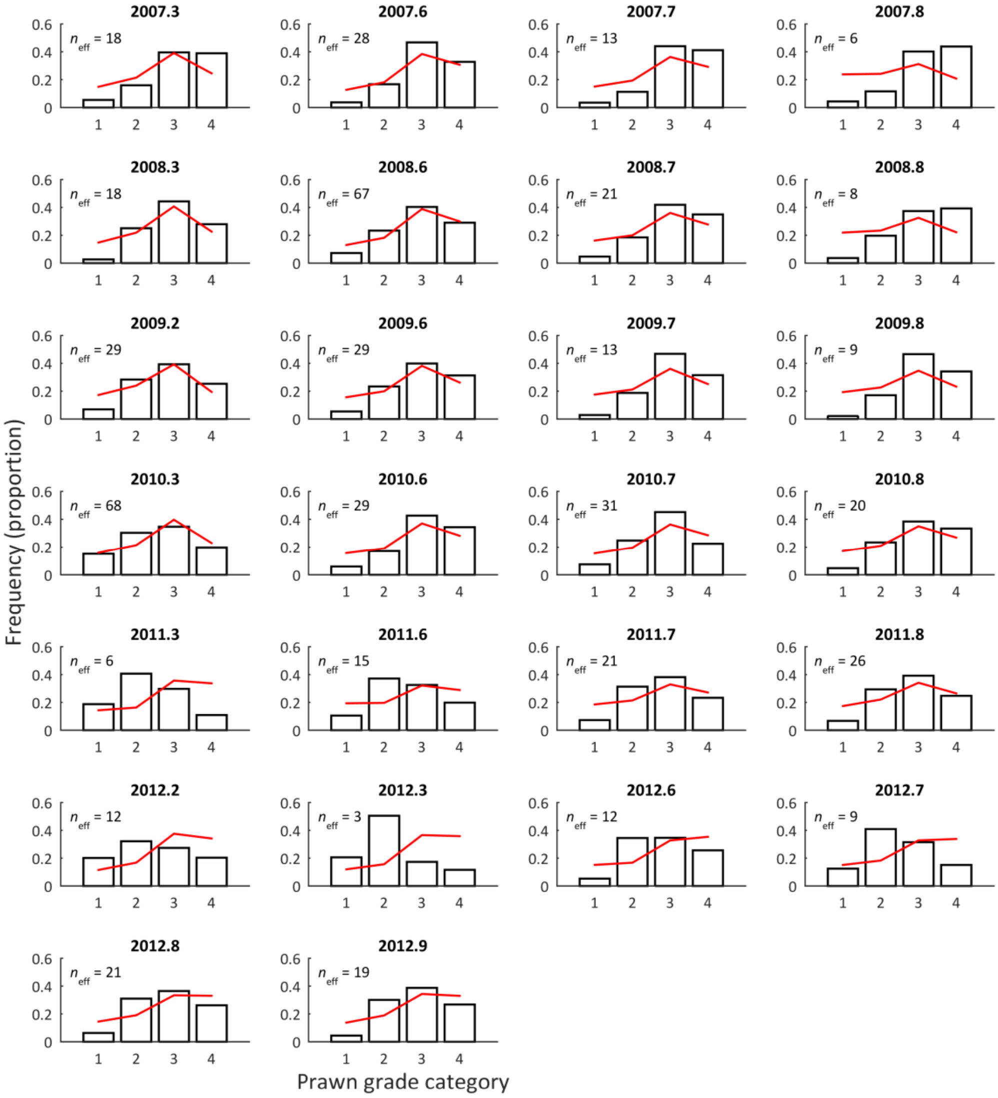


Figure F.14. Observed (bars) and predicted (red line) size-grade frequency distributions (proportions) in the GSVPF from 2007—2012. Size-grade categories: 1 = >20 lb^{-1}; 2 = 16-20 lb^{-1}; 3 = 10-15 lb^{-1}; 4 = <10 lb^{-1}. Labels refer to fishing year and month; n_{eff} indicates the effective multinomial sample size for each month.

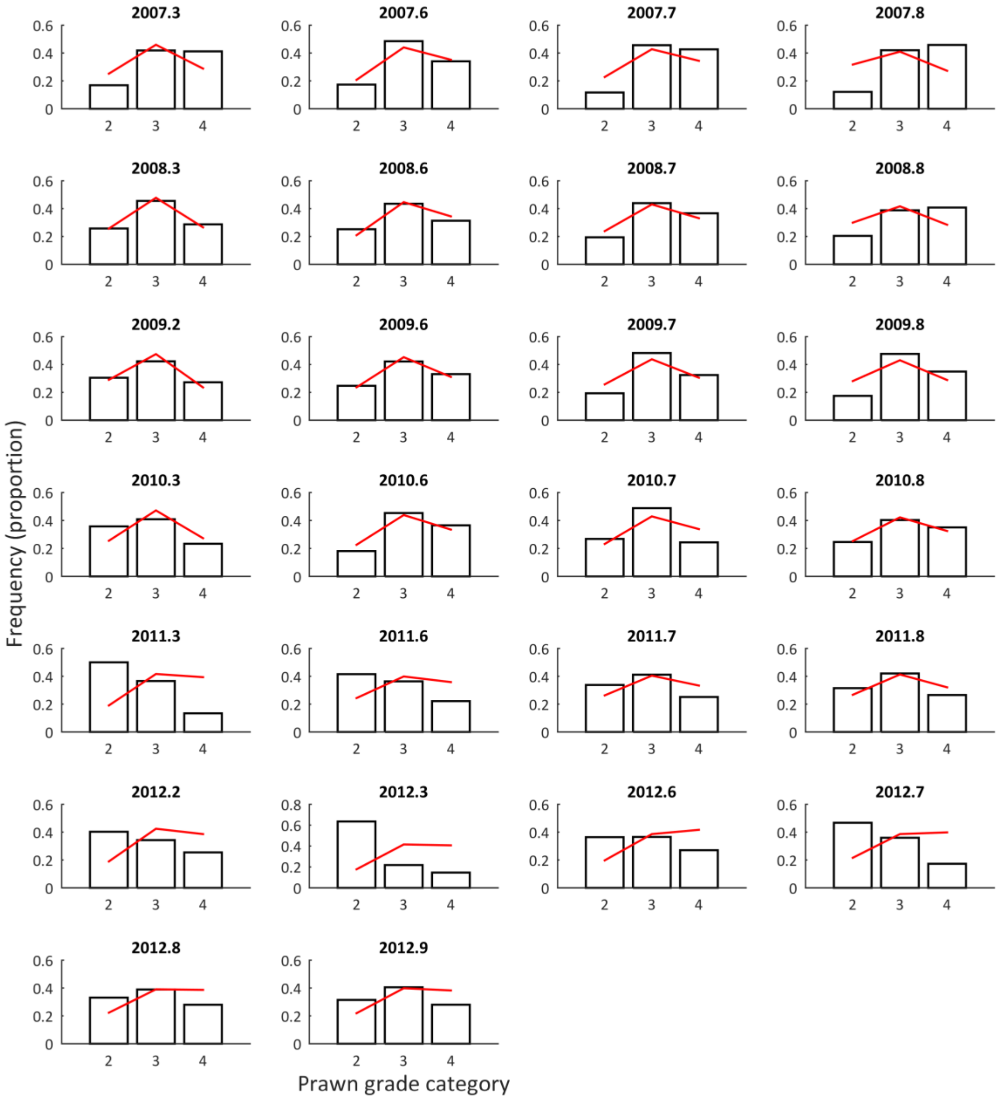


Figure F.15. Observed (bars) and predicted (red line) size-grade frequency distributions (proportions) in the GSVPF from 2007—2012 after omitting size-grade category 1 (>20 lb^{-1}). Size-grade categories: 2 = 16-20 lb^{-1}; 3 = 10-15 lb^{-1}; 4 = <10 lb^{-1}. Labels refer to fishing year and month.

Appendix G Supplementary plots – Spencer Gulf Prawn Fishery

G.1 Model input data

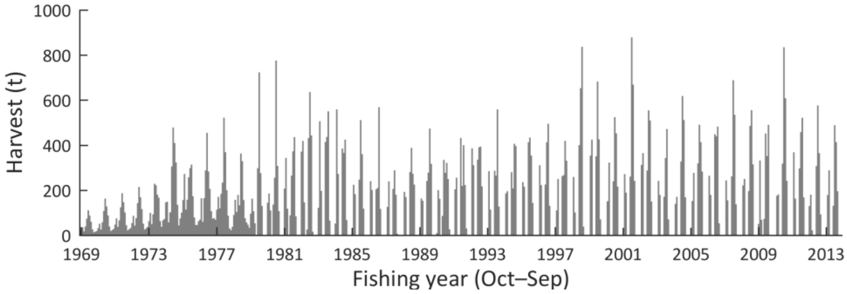


Figure G.1. Monthly harvest of WKP by the SGPF from 1968—2013.

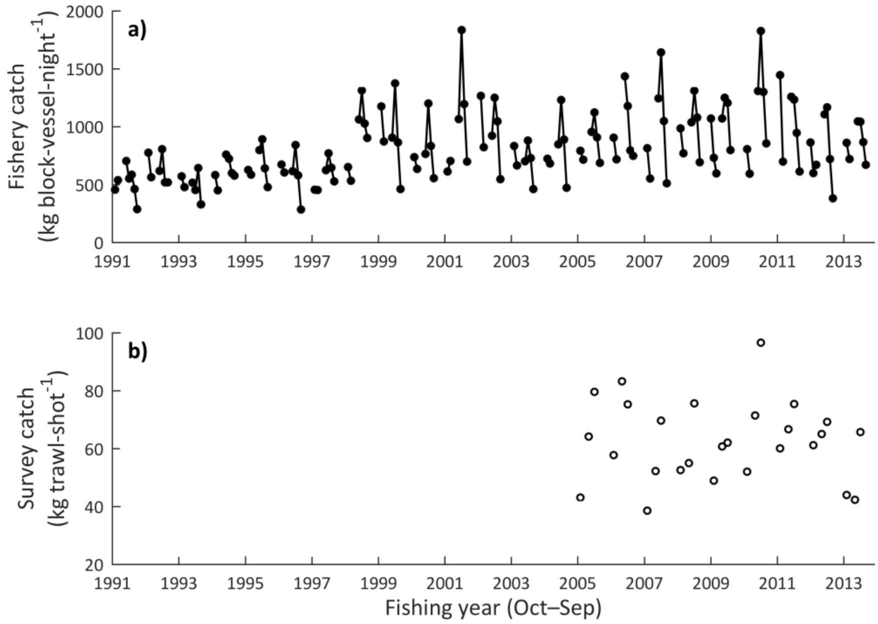


Figure G.2. Standardised mean a) fishery catches (1991—2013) and b) survey catches (2005—2013) in the SGPF.

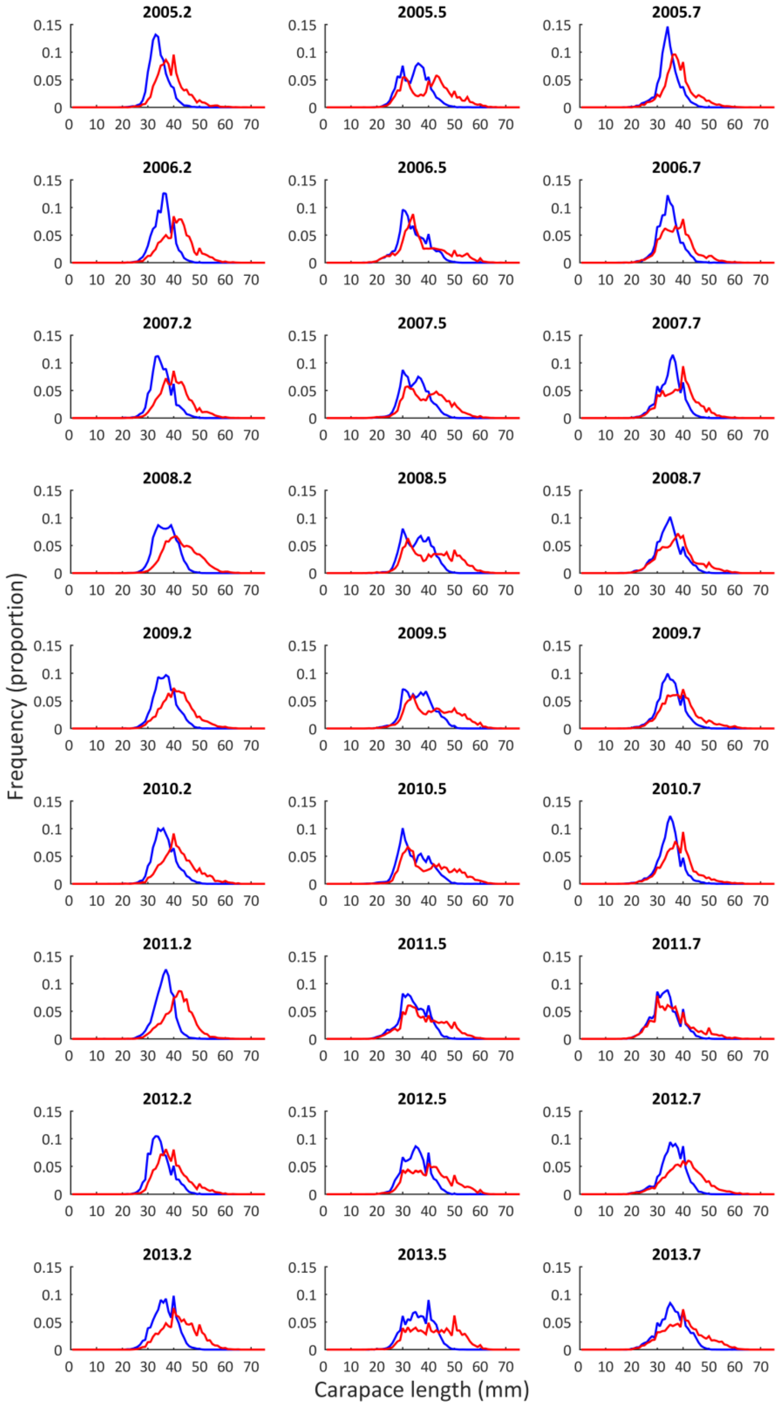


Figure G.3. Survey length-frequency distributions (proportions) for male (blue) and female (red) WKP in the SGPF from 2005—2013. Labels refer to fishing year and month.

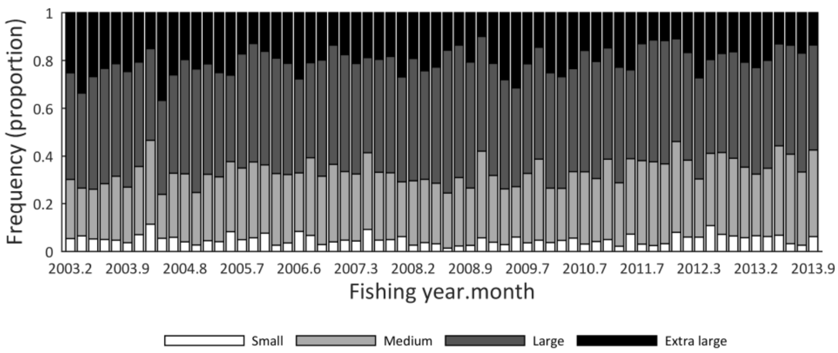


Figure G.4. Size-grade frequencies (proportions) in the SGPF from 2003—2013.

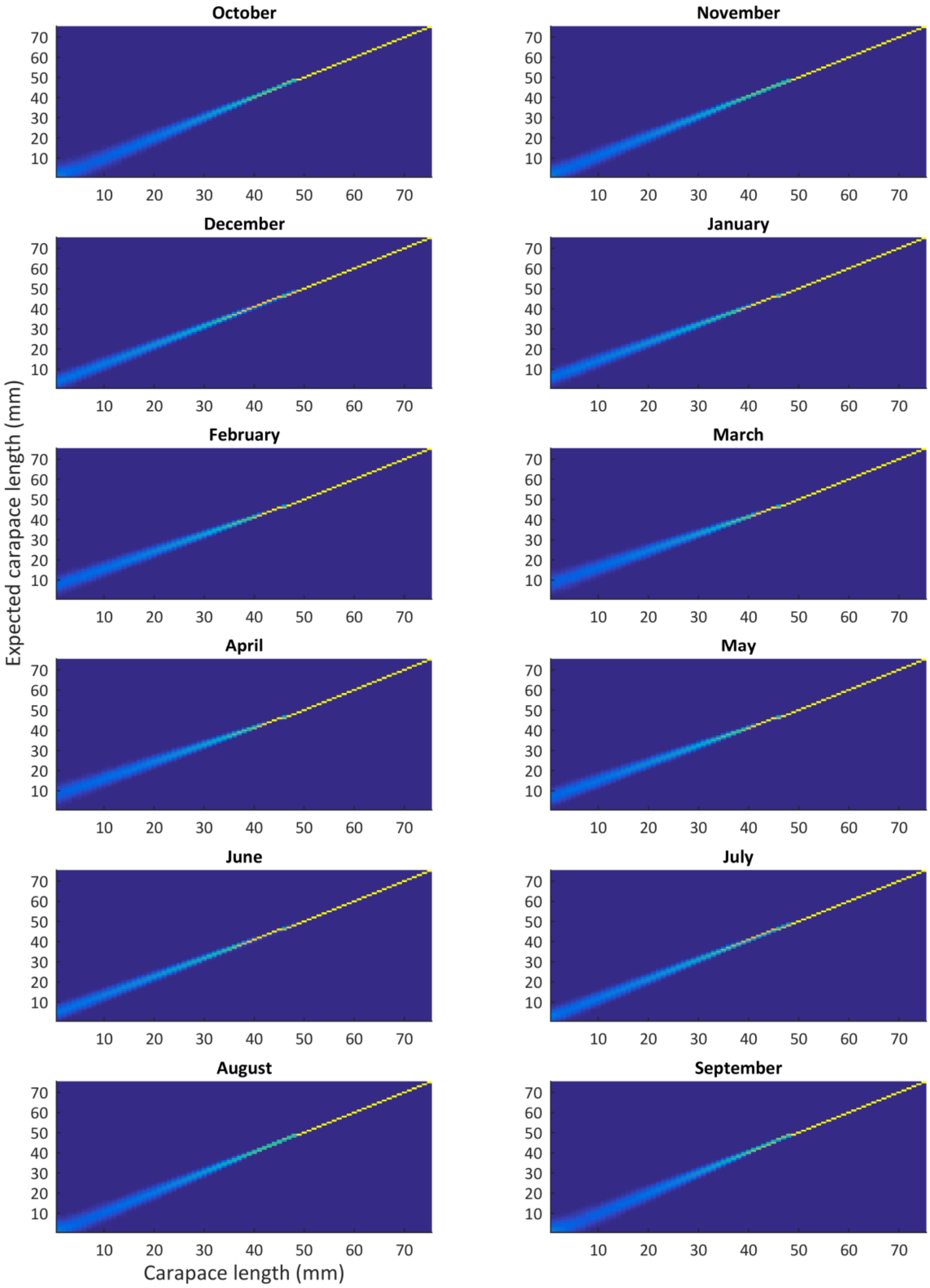


Figure G.5. Colour-scale visualisation of the size-transition matrix for male WKP in the SGPF. The scale from blue to red indicates increasing probability of prawns of carapace length-class *l'* in the previous month growing into a new length *l* over one month.

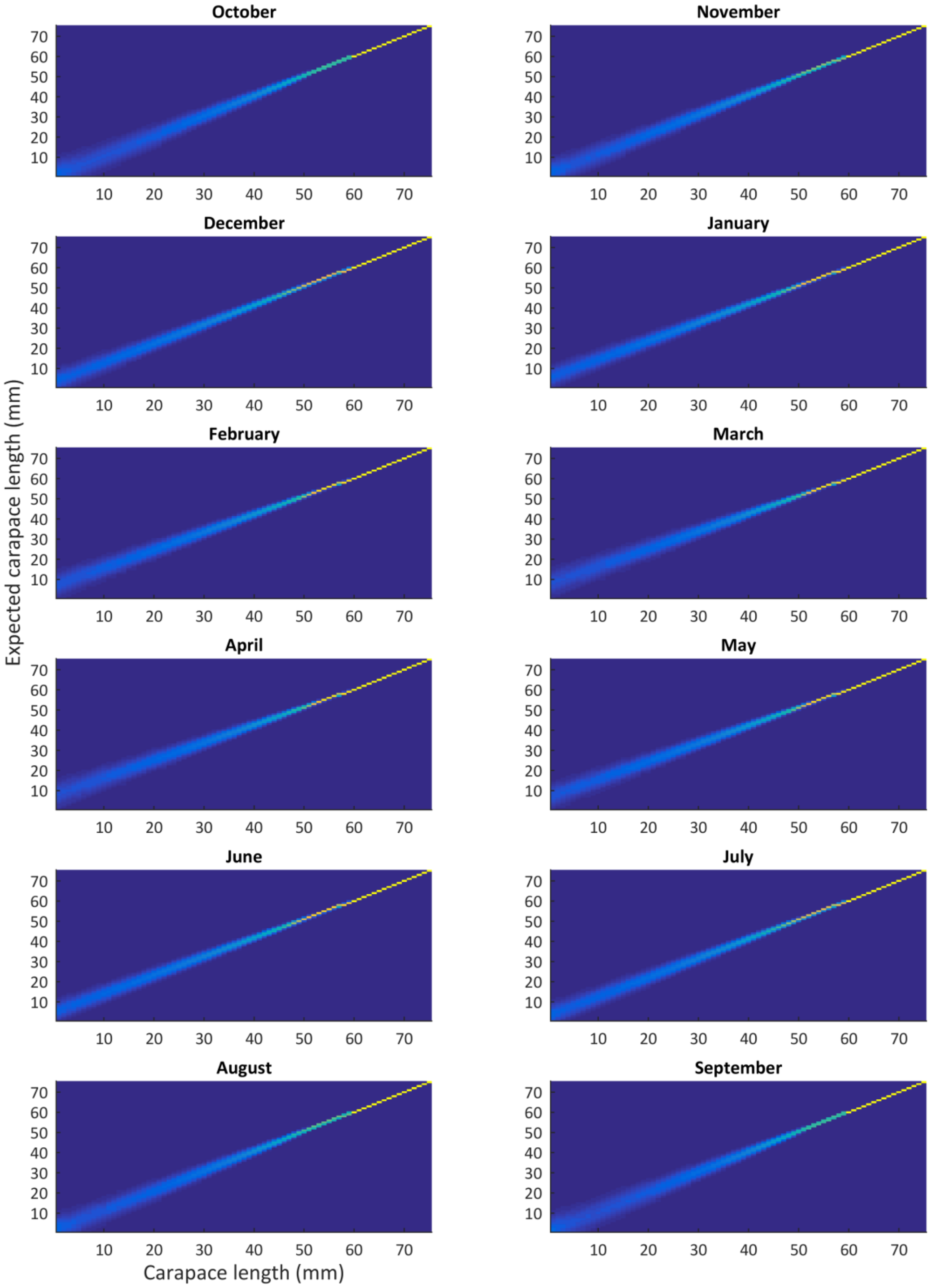


Figure G.6. Colour-scale visualisation of the size-transition matrix for female WKP in the SGPF. The scale from blue to red indicates increasing probability of prawns of carapace length-class *l'* in the previous month growing into a new length *l* over one month.

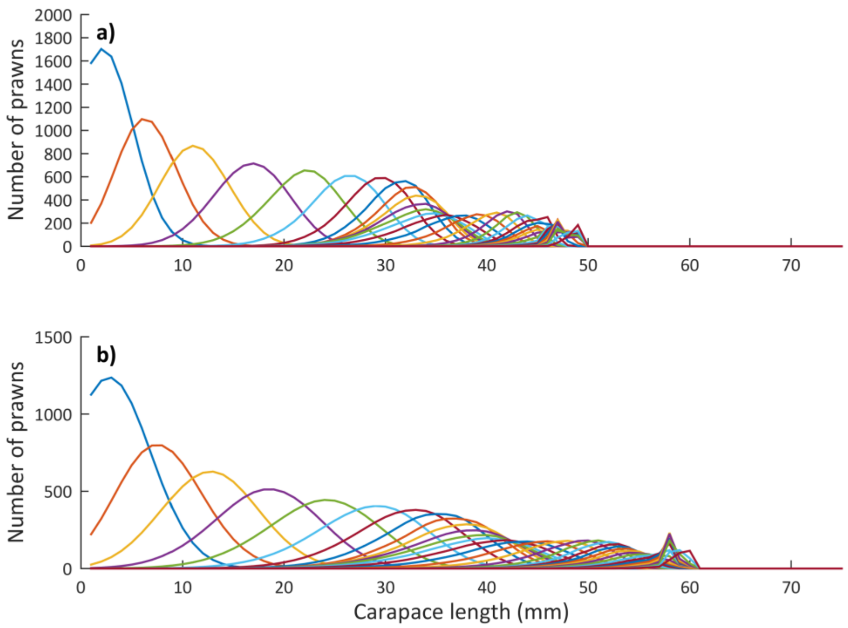


Figure G.7. Example growth of a cohort of a) male and b) female WKP in the SGPF. Each cohort initially comprised 10000 prawns of carapace length 1 mm in October. Cohort growth was based on size-transition matrices and natural mortality, and traced for 36 months, with each successive distribution representing a month.

G.2 Model output results

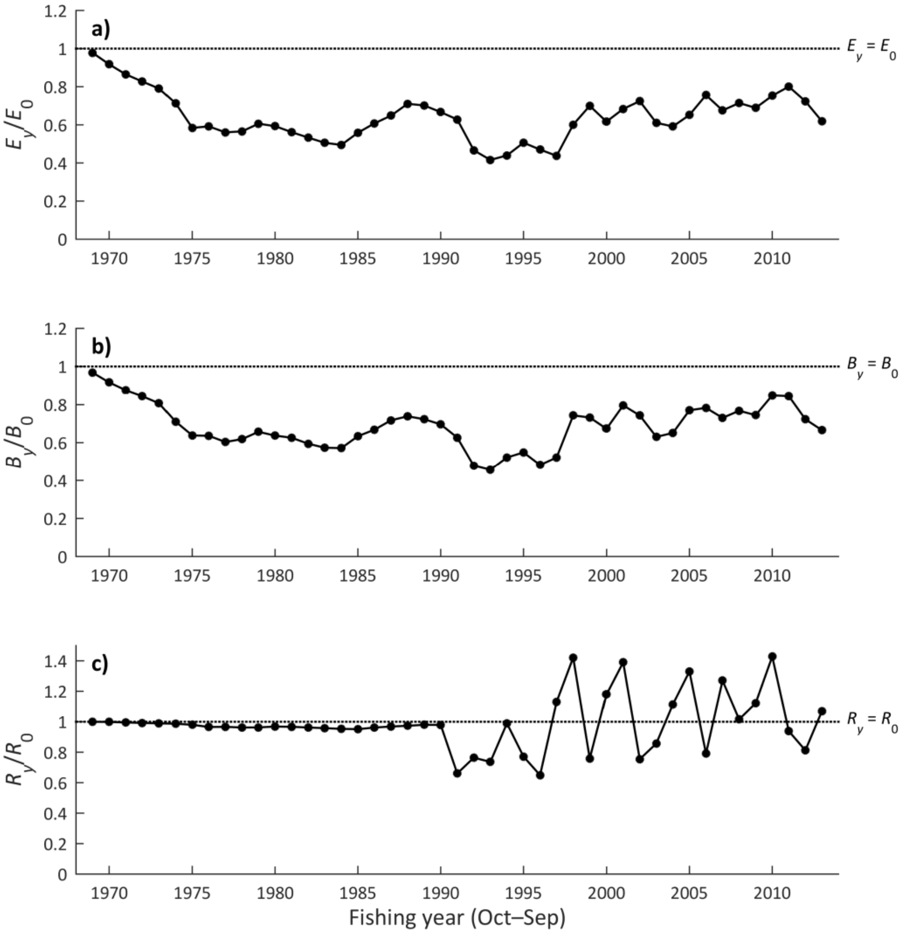


Figure G.8. WKP stock status annual plots for the SGPF from 1991—2013: a) spawning egg production ratio (E_y/E_0); b) exploitable biomass ratio (B_y/B_0); and c) recruitment ratio (R_y/R_0). The dotted reference line indicates the estimated level of the equilibrium virgin stock (i.e. t = 0 at 1969). Deterministic recruitment was modelled from 1969—1990 and stochastic (variable) recruitment thereafter.

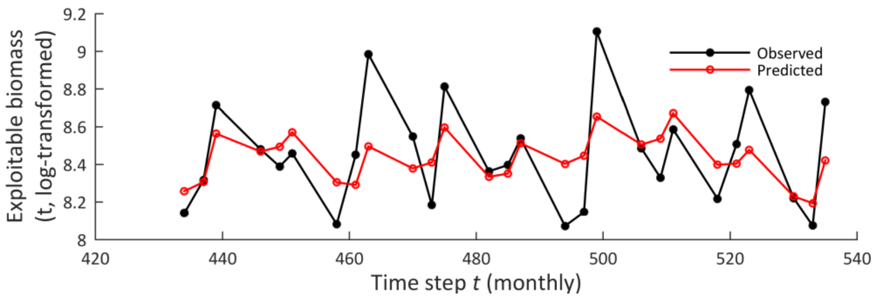


Figure G.9. Comparison of observed (survey) and predicted (model) WKP exploitable biomass by year-month in the SGPF.

G.3 Fishery catch rate diagnostics

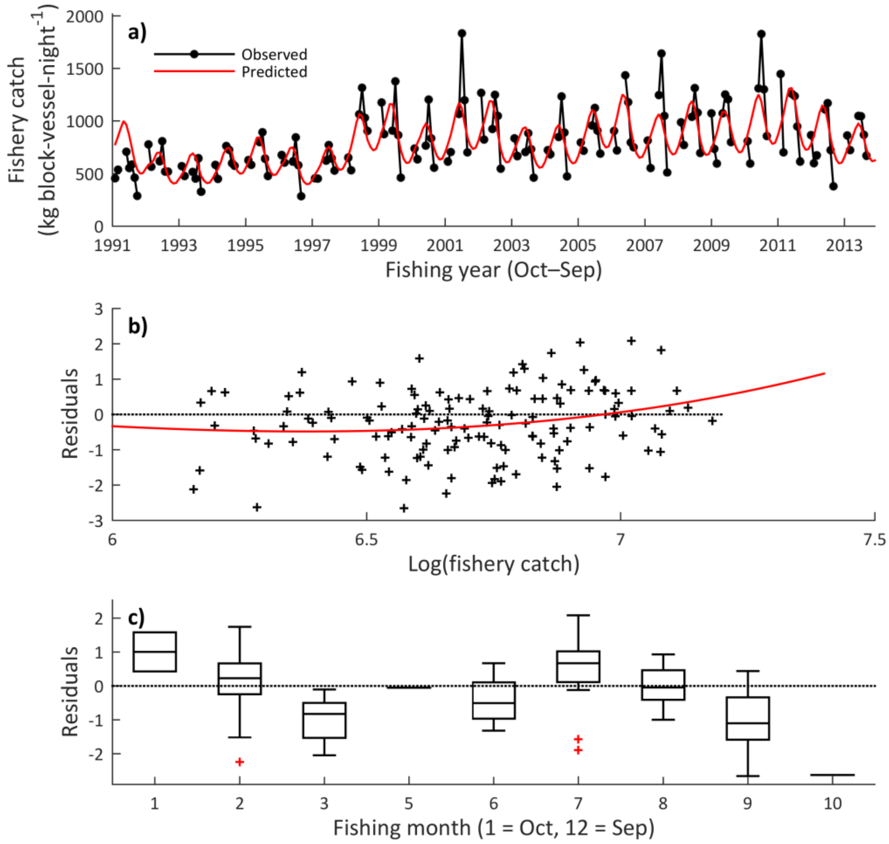


Figure G.10. Fishery catch rate fitted diagnostics for the SGPF: a) observed (standardised) and model-predicted catch rates each month from 1991—2013; b) standardised fitted values; and c) monthly standardised residuals.

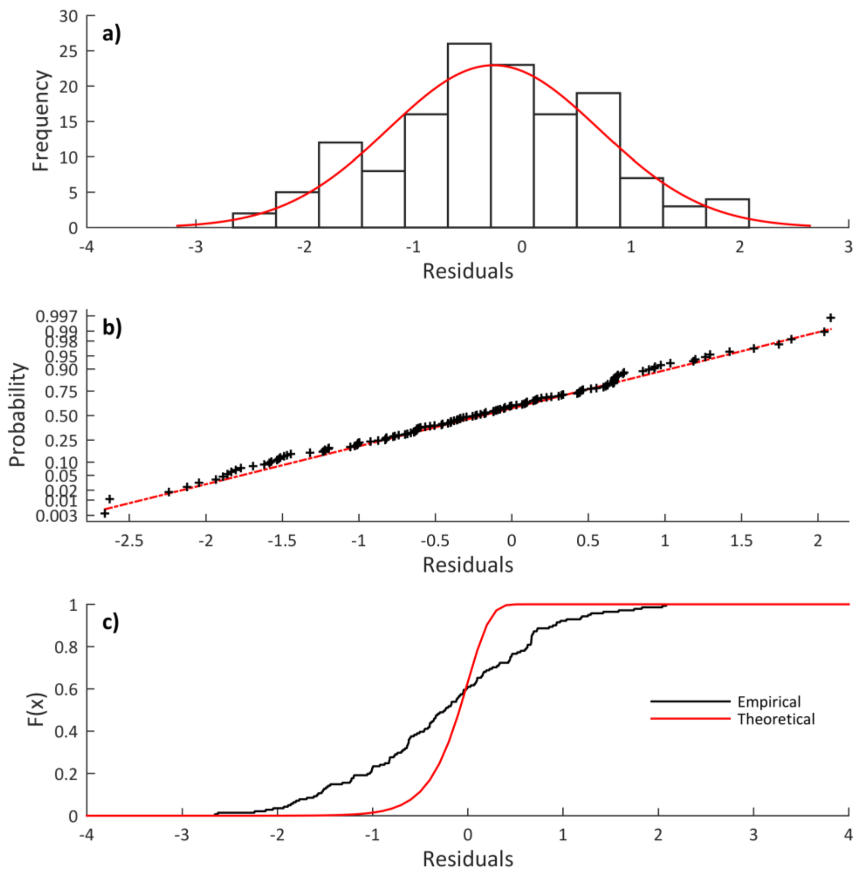


Figure G.11. Normality checks for fishery catch rates in the SGPF: a) histogram of standardised residuals; b) probability plot of standardised residuals; and c) cumulative density function of standardised residuals.

G.4 Survey catch rate diagnostics

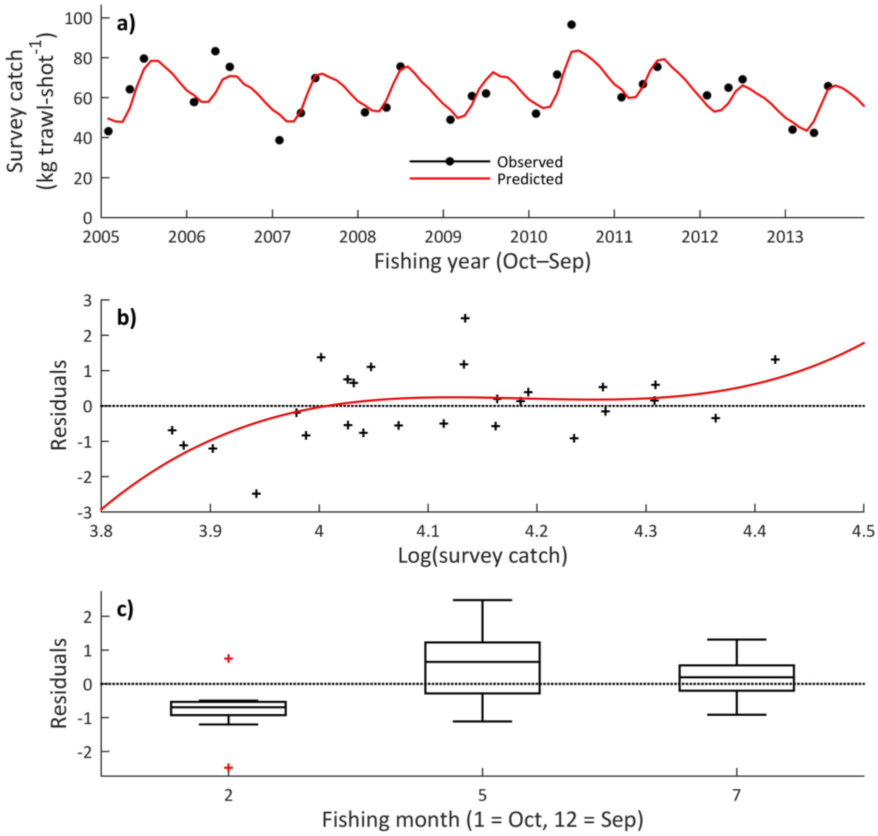


Figure G.12. Survey catch rate fitted diagnostics for the SGPF: a) observed (standardised) and model-predicted catch rates each month from 2005—2013; b) standardised fitted values; and c) monthly standardised residuals.

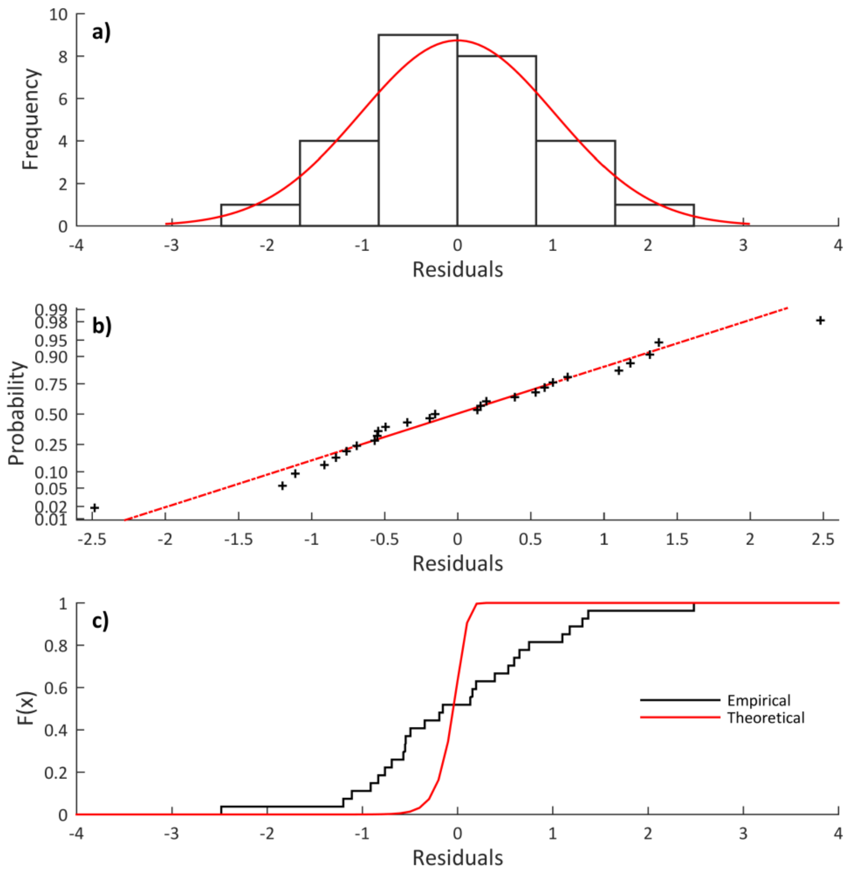


Figure G.13. Normality checks for survey catch rates in the SGPF: a) histogram of standardised residuals; b) probability plot of standardised residuals; and c) cumulative density function of standardised residuals.

Appendix H Supplementary plots – both fisheries

H.1 Model input data

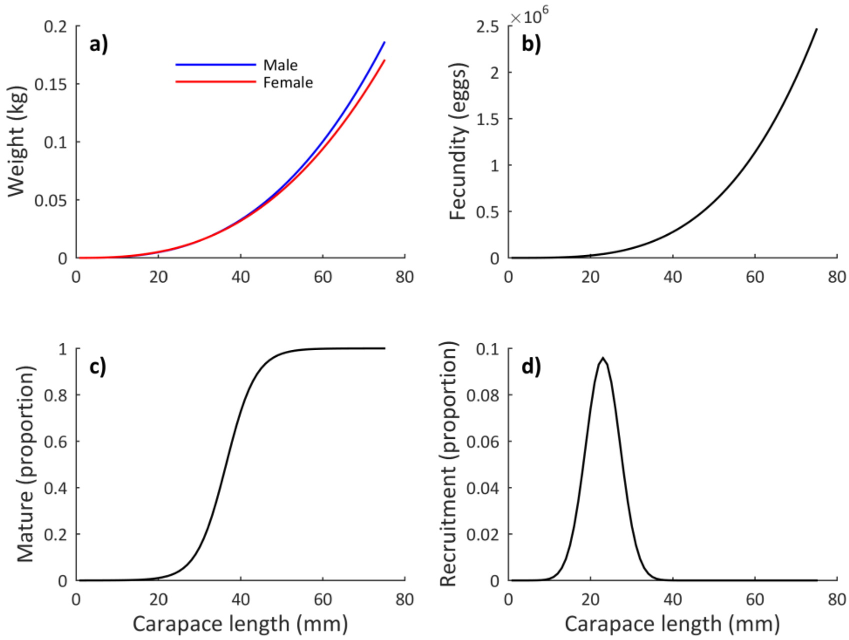


Figure H.1. Biological schedules for WKP relative to carapace length (both fisheries): a) weight of males and females; b) batch fecundity; c) maturity (proportion); and d) recruitment (proportion).