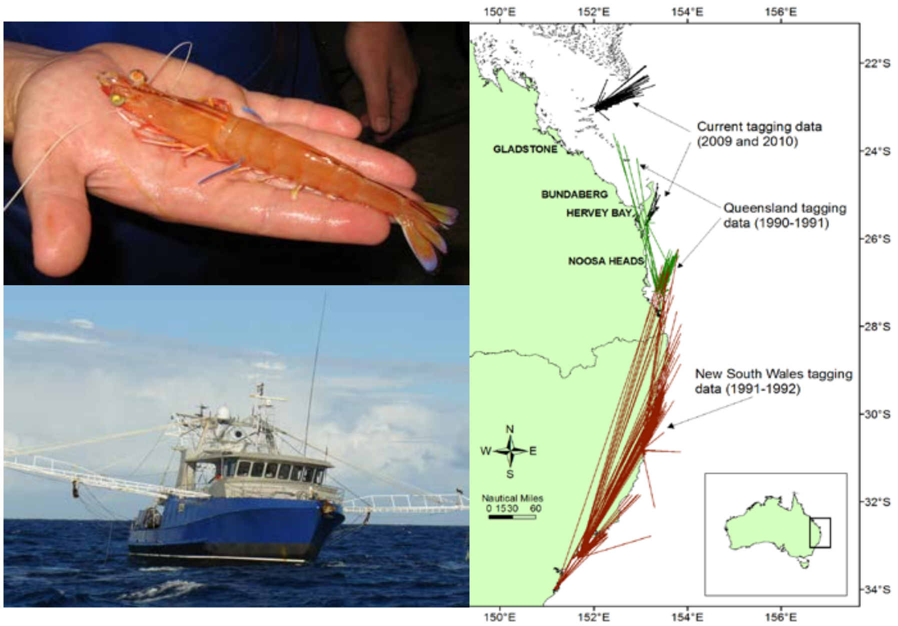
Biological and economic management strategy evaluations of the eastern king prawn fishery



A. J. Courtney, M. F. O'Neill, M. Braccini, G. M. Leigh, M. Kienzle, S. Pascoe[1],
A. J. Prosser, Y-G Wang[2], L. Lloyd-Jones[2], A. B. Campbell, M. Ives[3],
S. S. Montgomery[3] and J. Gorring

Department of Agriculture, Fisheries and Forestry, Queensland
[1]CSIRO Marine and Atmospheric Research
[2]School of Mathematics and Physics, University of Queensland
[3]New South Wales Primary Industries

Project 2008/019

Queensland Government

CSIRO

FRDC
FISHERIES RESEARCH & DEVELOPMENT CORPORATION

February 2014

ISBN: 978-0-7345-0439-5

Biological and economic management strategy evaluations of the eastern king prawn fishery
FRDC 2008/019
2014

This publication (and any information sourced from it) should be attributed to A. J. Courtney, M. F. O'Neill, M. Braccini, G. M. Leigh, M. Kienzle, S. Pascoe[1], A. J. Prosser, Y-G Wang[2], L. Lloyd-Jones[2], A. B. Campbell, M. Ives[3],S. S. Montgomery[3] and J. Gorring. Department of Agriculture, Fisheries and Forestry, Queensland, [1]CSIRO Marine and Atmospheric Research, [2]School of Mathematics and Physics, University of Queensland, [3]New South Wales Primary Industries. 2014 *Biological and economic management strategy evaluations of the eastern king prawn fishery*. Brisbane.

The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a statutory authority within the portfolio of the federal Minister for Agriculture, Fisheries and Forestry, jointly funded by the Australian Government and the fishing industry.

Researcher Contact Details

Name: Dr. Tony Courtney
Address: Level B1, Ecosciences Precinct, Joe Baker St, Dutton Park QLD 4102
Phone: 07 3255 4227
Fax: 07 3846 1207
Email: Tony.Courtney@daff.qld.gov.au

FRDC Contact Details

Address: 25 Geils Court
Deakin ACT 2600
Phone: 02 6285 0400
Fax: 02 6285 0499
Email: frdc@frdc.com.au
Web: www.frdc.com.au

Contents

List of tables

List of figures

List of acronyms

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
BRD	bycatch reduction device
CFISH	Queensland commercial fishery logbook database
CL	carapace length
CPUE	catch per unit effort
DAFF	(Queensland) Department of Agriculture, Fisheries and Forestry
EKP	Eastern king prawns (*Melicertus plebejus*)
E_{MEY}	Fishing effort required to achieve MEY
GBRMPA	Great Barrier Reef Marine Park Authority
GLM	generalised linear model
GPS	global positioning system
MEY	maximum economic yield
MVP	marginal value product
MSY	maximum sustainable yield
s.e.	standard error
TED	turtle excluder device

1 Non-Technical Summary

FRDC project number 2008/019. Biological and economic management strategy evaluations of the eastern king prawn fishery.

Principal Investigator:
Dr Tony Courtney, Principal Fisheries Biologist
Fisheries and Aquaculture, Agri-Science Queensland
Department of Agriculture, Fisheries and Forestry
Level B1, Ecosciences Precinct, Joe Baker St, Dutton Park, Queensland 4102
Email: tony.courtney@daff.qld.gov.au

OUTCOMES ACHIEVED TO DATE

- Eastern king prawns (EKP, *Melicertus plebejus*) are a valuable commercially-fished stock in Queensland and New South Wales, with a total annual landed value of about $45 million. An important outcome of the project was that it initiated a series of steering committee meetings that were made up of commercial fishers, GBRMPA, fishery economists, fishery managers and scientists from both states to focus on the fishery's performance, stock assessment and management. The project promoted collaborative research, assessment and management of the fishery.
- In its northern distribution (i.e., 22–24°S) the fishery is located over 100 km from the coast and the source of prawns caught in this area has been unknown. The study concluded the prawns most likely recruit from offshore reefs associated with the Capricorn-Bunker Islands. As a result, fishers and managers are now in a stronger position to develop and implement management measures, including closures, in this part of the fishery.
- Fishing power in the EKP fishery was found to have increased by 52% from 1989 to 2010, highlighting the need to take fishing power changes into account when reporting long-term trends in catch rates, assessing the stock and forecasting catch rates and biomass estimates.
- The project derived a new quantitative description of growth for *M. plebejus* by utilizing all available tag-recapture data from Queensland and New South Wales. Latitudinal and seasonal effects on growth were quantified. Growth rate falls to a minimum in winter, peaks in summer and declines with increasing latitude. This new description improves the accuracy of stock assessment and modeling of harvest strategies.
- An economic survey of the Queensland EKP fishery provided information on fixed and variable costs, total invested capital, gross value of product, average boat gross margin and total vessel costs. The data are used to comment on the profitability and economic viability of the fishery.
- The project evaluated 18 management scenarios put forward by fishers and managers from both states. These included one-monthly trawl closures, a cap on total fishing effort, and within-year catch rate control rules, as well as assumptions about annual increases in operational costs and fishing power.
- The project identified how profitability and sustainability of the EKP fishery could be improved by deriving estimates of MEY and E_{MEY} and presented these results to industry and managers at steering committee meetings. If current fishing costs remain steady or increase, total effort levels between 7000 and 20,000 boat-days will produce higher profit.

Northern recruitment dynamics

Eastern king prawns (EKP) are a commercially important species in Queensland and New South Wales, but little is known about the origins of prawns that are caught in the northern part of the fishery, which is located 100-170 km offshore from the central-southern Queensland coast (22°–24°S). We used a tag-recapture program, sample length-frequency data, commercial catch size grading data and logbook data, to examine spatial and temporal patterns in the prawn recruitment dynamics and concluded the prawns utilise offshore reefs associated with the Capricorn-Bunker Islands as nursery grounds. This is unusual as EKP utilise inshore estuaries, bays and seagrass areas as nurseries at higher latitudes.

The tagging and sample length frequency data were used to provide advice on the likely effects of a proposed closure in the northern part of the fishery, suggested by industry. The project found that the prawns being harvested in the proposed closure were at or close to the size at first capture required to maximise yield and value per recruit. As implementing the closure would increase the size at first capture, lowering the yield and catch value, and result in no obvious benefit to the fishery, we recommend that the closure not be implemented.

Economic survey

An economic survey of the EKP fishery was undertaken for the 2007/08 financial year to examine economic performance and develop a bioeconomic model of the fishery. The average invested capital (AIC) was $782,264 per license, of which the primary boat hull represented 57% and the license 17%. Average fixed costs (AFC) were $41,323 and variable costs (AVC) were $318,848 per vessel. Fuel made up about 60% of the variable costs. The average gross value of product (GVP), based on the estimated value of the reported logbook catches from the 26 vessels surveyed, was $378,674. Total Vessel Costs (TVC), estimated as the sum of the average fixed and variable costs, and labour costs, was $508,495 – indicating a loss of $129,821 per license. This was partly due to some companies with more than one vessel including land-based staff in their labour costs. However, using a lower fixed percentage (28%) of GVP for labour costs also indicated that the average license holder made a loss in the 2007/08 financial year. The prices and cost data were adjusted to 2010 equivalent levels for the bioeconomic modelling.

Bioeconomic modelling

Recently, some Australian fisheries have experienced reduced profits due to increased fishing costs and static landing prices. These economic circumstances have prompted fishery management towards more profitable procedures than maximum sustainable yield (MSY). The Australian eastern king prawn is one such fishery. Therefore new methodology was developed for stock assessment, calculation of model-based and data-based reference points and management strategy evaluation. Bioeconomic fishing data was standardised for calibrating a new length-spatial structured operating model. Results were compared against a standard delay difference biomass model. Simulations identified that a) boat numbers had to be reduced to secure more profitable fishing and reduce the risks of overfishing, b) alternative one-month spatial closures did little to improve profitability and c) catch rate reference points were effective for monitoring and management, but not with excessive fishing effort. If current fishing costs remain steady or increase, fishing between 7000 and 20,000 boat-days per year will produce higher profit. Decision makers need to consider the uncertainty, assumptions and political views affecting economic yields.

KEYWORDS: eastern king prawn, *Melicertus plebejus*, recruitment, tag-recapture, fishery economics, maximum sustainable yield, MSY, maximum economic yield, MEY, E_{MSY}, harvest strategy evaluations, fishing power, generalised linear model, GLM, linear mixed models.

2 Acknowledgements

The project was largely funded by FRDC (Project number 2008/019) and we appreciate the support provided by FRDC, especially Crispian Ashby, Annette Lyons and Carolyn Stewardson.

We are grateful for the support and advice provided by the project steering committee members, Lew Williams (DAFF), Joshua Maroske (DAFF), Eddie Jebreen (DAFF), Tom Kompas (Australian National University), Cathy Dichmont (CSIRO), Stephen Murphy (Industry), David Sterling (Industry/Research), Rachel Pears (GBRMPA), Fiona Hill and Darren Hale (New South Wales Fisheries Management).

Thanks to Stephen Murphy and the Australian Ocean King Prawn Company for providing their extensive prawn catch grading data (i.e. > 10 years of daily catch grading data from five vessels) and for making their trawler *Somatina* available for the 2009 charter. We thank skipper Terry Muller and crew for their cooperation and seamanship, and John Lasek (volunteer, Australian Maritime College) for his assistance, during the charter. Thanks also to skipper Barry Ehrke and crew Rod Hansen for their professionalism during the 2010 charter of the research vessel *Gwendoline May*. Prawn sampling and tagging in the Great Barrier Reef Marine Park were conducted under the GBRMPA permit G08/28853.1. An antibiotic (Oxytetracycline) was applied to the prawn tag wounds under APVMA permit number PER11898. We are grateful for the support from over 30 fishers and processors who provided us recaptured tagged prawns and details of their recapture date and location.

Kate Yeomans, Nadia Engstrom, Susan Theiss and Prasadini Salgdo (DAFF) provided CFISH logbook data and advice. David Mayer and Kerri Dawson (DAFF) provided statistical support. Martin Perkins (QSMA) and Michael Woods (Industry) provided data on prawn prices. We also thank DAFF staff Ben Bassingthwaighte, Donna Buckley, Debra Davis, Paul Hickey, Kayleen Giezendanner and Faye Turner for administrative, financial and human resource management support and advice.

3 Background

The eastern king prawn (EKP) fishery is one of Queensland's most valuable commercially-fished stocks. Logbook data indicate that about 2400 tonnes of EKP were caught in Queensland annually from 2008 to 2011 (excluding Moreton Bay). An additional 400-600 t were caught annually in New South Wales over this time period. There are a number of issues that need to be addressed to improve the value, sustainability and profitability of the stock.

Eastern king prawns, and their fishery, occur over a very large area from about 20-41°S on the Australian east coast. This is partly because they are highly mobile, unlike most prawn species. Tagging studies have shown that EKP can migrate over 1000 km, usually in a northerly direction along the east coast. They also differ from most prawn species by occurring over a very wide range of depths, from 5-10 m in Moreton Bay to about 250 m in waters near the Swain Reefs. They are the largest of Australia's endemic penaeid prawns and can reach 30 cm in total length.

While much of the biology and population dynamics of EKP have been described, little is known about the stock in its northern distribution (i.e., 22-24°S). About 200 tonnes of EKP are caught annually in this area between, mainly between North Reef and the Swain Reefs, which are located approximately 100 km and 170 km offshore, respectively. The source of recruits to this offshore area is unknown. Tagging studies conducted from known recruitment areas further south, such as the Wide Bay Bar (26°S), Moreton Bay (27°S) and further south in New South Wales, suggest that very few prawns in these areas migrate to the North Reef-Swain Reefs' fishery. There is the possibility that most of the EKP caught in the area recruit from nearby offshore reefs, which is unusual for penaeids, but not unique. The typical life cycle of prawns usually involves juveniles migrating from inshore estuarine, mangrove or seagrass areas to deeper offshore waters, but this may not be the case in the northern part of the EKP fishery, which is located relatively far offshore. It would improve our understanding of the stock and possibly reduce the risk of overfishing prawns in this area if we had a clearer understanding of the source of these recruits. This project proposes to study the recruitment dynamics of the stock in its northern distribution.

Based on the assessment by O'Neill *et al.* (2005), the eastern king prawn stock has continued to receive high levels of annual fishing effort in Queensland. This is partly attributed to high fuel prices making it less attractive for fishers to travel/steam to north Queensland to the tiger/endeavour prawn grounds, and partly due to the buoyant prices commanded by EKP. Because EKP are a relatively large prawn species, their domestic price appears to be partly shielded from the low prawn prices that have resulted from the importation of aquacultured vannamei prawns. In addition to receiving high effort, the fishing power of the average vessel operating in the EKP fishery has increased substantially in recent years (i.e., average vessel fishing power in 2004 was 1.423 times that of the average vessel in 1989; O'Neill and Leigh (2006)). This is mainly due to smaller, less-powerful vessels leaving the industry since the introduction of the Fisheries (East Coast Trawl) Management Plan 1999, thus leaving larger more powerful vessels to operate. The result of high effort levels combined with substantially increased fishing power, has resulted in the Queensland EKP stock experiencing record high levels of fishing mortality, which has created concerns of overfishing. The Queensland trawl fishery managers are concerned about the level of effort applied to the stock and are considering a range of management measures, including closures, to reduce effort and the risk of recruitment overfishing. This project proposes to examine the economics of the fishery and simulate these management strategies with the objective of providing the managers with advice.

4 Need

Stock assessment of the EKP fishery, and the subsequent advice to management and industry, could be improved by addressing a number of issues.

The recruitment dynamics of EKP in the northern (i.e., North Reef to the Swain Reefs) parts of the fishery need to be clarified. Fishers report that the size of the prawns from these areas when they recruit to the fishing grounds is resulting in sub-optimal sizes/ages at first capture, and therefore localised growth overfishing.

There is a need to assess alternative harvest strategies of the EKP fishery, via computer simulations, particularly seasonal and monthly or lunar-based closures to identify scenarios that improve the value of the catch, decrease costs and reduce the risk of overfishing, prior to implementing new management measures.

The project is highly relevant to FRDC priorities and directly addresses the FRDC R&D 2005-2010 Plan, namely Program 1 Natural Resources Sustainability, Challenge 1 – Natural Resource Sustainability "Maintain and improve the management and use of aquatic natural resources to ensure their sustainability".

The proposal directly addresses the QFIRAC 2007 R&D priorities for Trawl Fisheries which specifically refer to "Undertaking management strategy evaluations for the Eastern King Prawn fishery, particularly the potential for seasonal closures…".

It also addresses the Queensland TrawlMAC "high" research priorities in relation to improving our understanding of the stock-recruitment relationships and undertaking management strategy evaluations.

In summary, there is a strong need for the project, which addresses the high research priorities identified by FRDC, QFIRAC and the Queensland TrawlMAC. It is focused on one of Queensland's most valuable fished stocks, eastern king prawns.

5 Objectives

1) Investigate the recruitment dynamics of eastern king prawns in their northern-most distribution (i.e., the North Reef-Swain Reefs area)
2) Undertake an economic analysis of the eastern king prawn fishery and determine the optimum yield and effort for profitability
3) Develop (computer) models of the eastern king prawn fishery that evaluate alternative harvest strategies, as identified by the fishery managers and fishers, and provide advice on the efficacy of each strategy in achieving biological and economic management objectives.

6 Methods

The project methods were developed and applied in discrete steps associated with each of the above objectives. Many of the findings and results from Objective 1 (northern recruitment dynamics) and Objective 2 (economic analysis) were used in modelling to address Objective 3 (modelling harvest strategies). Details of the methods are provided in the Appendices (Sections 15–23) and therefore only brief descriptions are provided here.

6.1.1 Recruitment dynamics in the northern part of the fishery (for details see 15 Appendix 3. Recruitment dynamics of eastern king prawns in their northern distribution (Objective 1))

We undertook a tag-recapture study and analysed sample length frequency data, commercial catch grading data and logbook data to infer temporal and spatial patterns in recruitment of EKP in their northern distribution (22º-24ºS) in Queensland offshore coastal waters.

A total of 3766 EKP were tagged and released and length-frequency data were obtained from 12,485 prawns sampled from 83 sites during two research charters undertaken in the area in 2009 and 2010 (Figure 6-1). These data provided information on the likely origins of the prawns, their movements and recruitment to the fishery. We also analysed a large commercial catch grading dataset provided by Mr. Steve Murphy from the Australian Ocean King Prawn Company. The grading data consisted of information on over 394,000 five kilogram boxes of prawn catch (i.e., ~2000 t) that were allocated to seven commercial size grades by five vessels over approximately 10 years. As the data were recorded daily, they could be linked to each vessel's location, using logbook data, thus providing information on the temporal and spatial recruitment dynamics of the prawns in the region. We also examined temporal and spatial trends in logbook data to determine patterns in recruitment.

6.1.2 Economic survey and analysis of the eastern king prawn fishery (for details see 16 Appendix 4. Economic survey of the eastern king prawn fishery (Objective 2))

Economic data are required by fishery managers for setting economic objectives and reference points, such as maximum economic yield (MEY). They can also be used for monitoring the value of fishery licenses and fishing businesses over time. Despite their importance, relatively few economic data are available for the Queensland's commercial fisheries. Previous economic studies include those of Moxon and Quinn (1984), Reid and Campbell (1999) and Taylor-Moore *et al.* (2000).

In 2009 Fisheries Queensland initiated another economic survey of the state's commercial fishing licence holders for the 2007-08 financial year. The study was posted to all Queensland commercial fishers who were asked to provide information on the fixed (i.e., capital, license, wharfage, insurance, etc.) and variable (labour, fuel, maintenance) costs associated with each commercial sector (i.e., trawl, net, line and crab). Spatial information on seafood sales and port usage were also sought to determine how the regional distribution of fishing businesses has changed. The survey also sought details on the number of years each licence holder worked in the industry, vessel characteristics and issues that fishers felt were important to the industry. The survey was forwarded to all 1317 Queensland licence holders.

Disappointingly, only 103 responses were received (i.e., < 10%) which significantly reduced the value of the data.

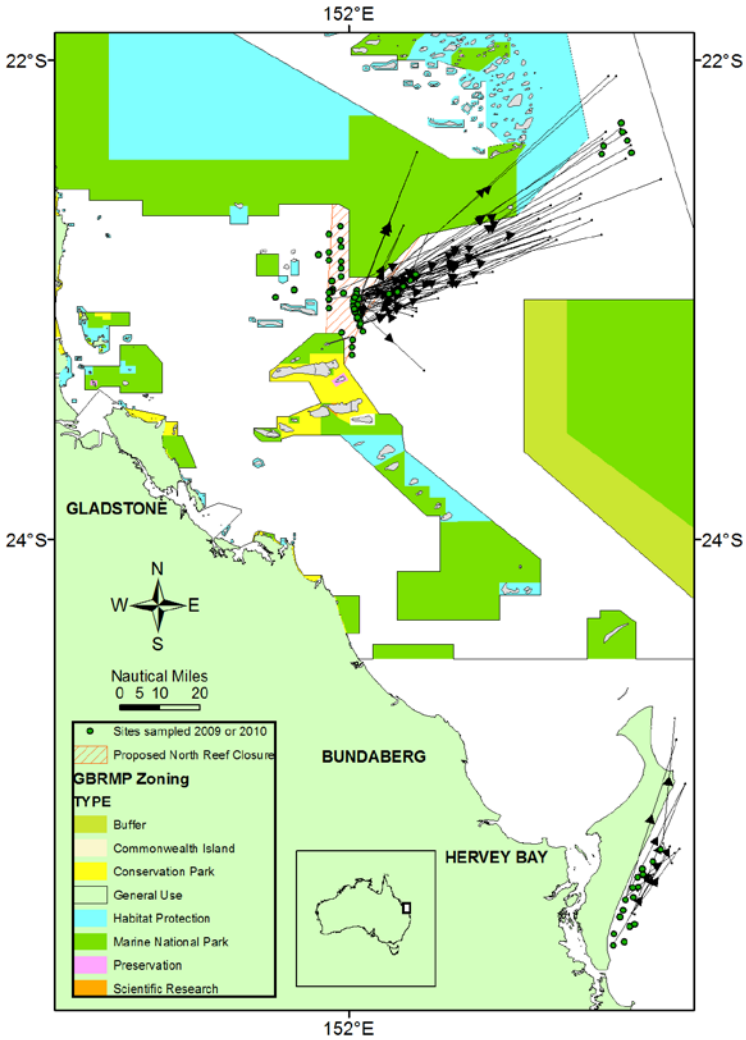


Figure 6-1. Sampling sites and prawn movements from the tagging study in the northern part of the eastern king prawn fishery, as a result of two research charters in 2009 and 2010. Most commercial trawling for EKP occurs well offshore in this region (i.e., > 100 km) and the source of juveniles that recruit to the fishery has been unclear. A proposed closed area suggested by fishers is also shown.

A total of 19 otter trawl licence holders responded to the survey. Of these, 14 were identified as primarily targeting EKP, and therefore their data were deemed highly relevant to the current study. On closer examination of the data, however, only 12 of these vessels provided adequate information. To increase the sample size, project staff obtained completed surveys from an additional 12 EKP fishers in 2010, bringing the number of licence holders who provided data to 24. All survey data relate to the 2007-08 financial year. Logbook records indicated that these 24 participants contributed about 20% of the total annual catch and effort in EKP fishery.

6.1.3 *Length-spatial structured model (for details see 17 Appendix 5. Bioeconomic modelling of the eastern king prawn (Melicertus* plebejus) *fishery)*

The EKP population dynamics tracked monthly numbers (*N*) and biomass (*B*) of prawns by their sex (*s*), length (l) and spatial region (*r*) (Equation 1). Every month (*t*) the biological processes of regional mortality, growth, movement and recruitment were accounted. The model was run in two phases: (i) historical estimation of the EKP stock from 1958 to 2010 and (ii) simulations of EKP parameter values and uncertainty to evaluate reference points and management procedures.

$$N_{l,r,t,s} = \exp\left(-M\right)\sum_{r'} \mathrm{T}_{r,r',t-1}\sum_{l'} \Xi_{l,l',r',t-1,s}\left(1-v_{l',r'}u_{r',t-1}\right)N_{l',r',t-1,s} + 0.5R_{l,r,t} \qquad (1)$$

In order to realise the operating model, parameters were estimated to calibrate the model to regional standardised catch rates and size-composition data. Primary importance was placed on fitting the abundance (standardised catch rates) data well (Francis 2011). Effective sample sizes were estimated for scaling multinomial likelihoods in order to calibrate to the size composition data. Prior fitting information was given for estimating uncertainty in stock recruitment steepness (*h*), natural mortality (*M*) and annual recruitment variation (η).

The calibration process compared both maximum likelihood estimation and Markov Chain Monte Carlo sampling (MCMC). The MCMC used a multivariate vector-jumping Metropolis-Hastings algorithm (Gelman *et al.* 2004). The MCMC started at the maximum likelihood parameters, with one hundred and ten thousand samples run to estimate the parameter covariance matrix and customise the vector jumping to ensure optimal acceptance ratios of about 0.2 (Gelman *et al.* 2004). A further two million samples were run with fixed covariance. To minimise autocorrelations, parameter estimates were based on one thousand posterior samples thinned from the last two million simulations. The R-coda programming package was used to analyse and confirm valid diagnostics for MCMC (R Development Core Team 2012). Goodness-of-fit plots were examined to evaluate model fits. The maximum likelihood parameter estimates and their covariance matrix (from MCMC) were stored for estimating reference points and running simulations.

6.1.4 *Delay difference model (for details see 17 Appendix 5. Bioeconomic modelling of the eastern king prawn (*Melicertus plebejus*) fishery)*

The Deriso-Schnute delay difference model was used in this study to assess the eastern king prawn stock as a single-entity across Queensland and New South Wales waters (Quinn and Deriso 1999; Schnute 1985). The model simplified the population mathematics and provided a comparison against the more complex length-spatial model. The model also allowed for easier testing of key data uncertainties. Historically, the Deriso-Schnute delay difference model was used to assess eastern king prawns in 2001 and 2004 (Ives and Scandol 2007; O'Neill *et al.* 2005). The model also assessed Torres Strait tiger prawns (O'Neill and Turnbull 2006) and Northern Australia’s tiger prawns (Dichmont *et al.* 2001). These past assessments were all independently reviewed and positively accepted.

The dynamics of the delay difference model operated on monthly time steps *t*:

$$B_t = (1+\rho)B_{t-1}s_{t-1} - \rho s_{t-1}s_{t-2}B_{t-2} - \rho s_{t-1}w_{r-1}R_{t-1} + w_r R_t \qquad (2)$$

where B was the exploitable biomass of eastern king prawns (kg), ρ was the growth parameter, s was prawn survival, w was the mean weight kg of recruiting prawns and R was the number of newly recruited prawns. Recruitment R was assumed to follow an annual Beverton and Holt function with lognormal deviations multiplied by a monthly recruitment probability calculated from a normalised von Mises directional distribution

Both whole-of-fishery and region-4-survey standardised time series of catch rates were tuned as abundance indices assuming a lognormal distribution. Four different model fits were considered examining assumptions on natural mortality, historical harvest and fishing power. Bias corrected confidence intervals on model outputs were generated from bootstrapping (Haddon 2001).

*6.1.5 Economic model and parameters (for details see 17 Appendix 5. Bioeconomic modelling of the eastern king prawn (*Melicertus plebejus*) fishery)*

The economic model calculated net present value (NPV) following the methods for assessing Australia's Northern Prawn Fishery (Punt *et al.* 2010). The NPV objective function summed profits over model future-projections:

$$\text{NPV} = \sum_{y=1}^{T-1} \frac{\pi_y}{(1+i)^{y-1}} + \frac{[\pi_T / i]}{(1+i)^{T-1}},$$

where i was the annual interest (discount) rate, π_y the profit during year y, and π_T the profit in terminal year T (last year of the future projection). The function was assumed to be in equilibrium in the terminal year and hence the level of profits in this year continued indefinitely.

Annual profit was calculated as catch value minus variable and fixed cost components:

$$\pi_y = \sum_r \left(\sum_t \left(\sum_l v_{r,t,l} C_{r,t,l} - \Omega^{\text{V}}_{r,t} \right) + \bar{B}^{by}_r E_{r,y} - \left(\Omega^{\text{F}}_{r,y} \frac{E_{r,y}}{\bar{d}_r} \rho \right) \right),$$

where $v_{r,l,t}$ was the average EKP prawn price in region r, time-month t and length class l, $C_{r,t,l}$ was the EKP harvest tonnage, $\Omega^{\text{V}}_{r,t}$ was the total variable costs, $\bar{B}^{by}_r$ was the average by-product value ($) taken each boat day, $E_{r,y}$ was the total annual boat days fished, Ω^{F}_y the average annual fixed costs, $\bar{d}$ was the mean number of days fished per boat year and ρ was the fraction of fixed costs allocated to the EKP fishery. The division by $\bar{d}_r$ allowed the annual number of vessels to change based on profitability.

Variable costs $\Omega^{\text{V}}_{r,t}$ were calculated by region r and time-month t. This included the proportional share for fishing labour (c_L), proportional cost of packaging and marketing (c_M), repairs and maintenance cost per boat-day (c_K), fuel cost per boat-day (c_F), and other incidental costs per boat-day (c_O):

$$\Omega^{\text{V}}_{r,t} = \sum_l \left(c_{L_r} v_{r,t,l} + c_{M_r} \right) C_{r,t,l} + \left(c_{K_r} + c_{F_r} + c_{O_r} \right) E_{r,t}.$$

Average annual fixed costs $\Omega^{\mathrm{F}}_{r,y}$ were calculated using regional vessel costs (W_r), and opportunity (o) and deprecation (d) rates on average total investment value per vessel ($K_{r,y}$):

$$\Omega^{\mathrm{F}}_{r,y} = \left(W_r + (o+d)K_{r,y}\right).$$

The economic parameter values for the above equations were treated as representative after comparison with basic fleet descriptors and other fisheries, and after steering committee review (Table 6-1).

Table 6-1. Input parameter values and their 95% confidence intervals for the economic model.

Parameters		New South Wales		Queensland	States combined (weighted mean)
Variable costs:					
Labour (*cL*: proportion of catch $)		0.29 (0.2 : 0.39)		0.29 (0.2 : 0.39)	0.29
Packaging (*cM*: $ kg^{-1})		0.41 (0.28 : 0.54)		0.41 (0.28 : 0.54)	0.41
Repairs (*cK*: $ boat-day^{-1})		288.63 (201.26 : 415.74)		407.46 (320.82 : 520.1)	384
Fuel (*cF*: $ boat-day^{-1})	Reg. 1	526.79 (476.8 : 576.37)	Reg. 4	546.35 (494.58 : 597.76)	619
Fuel (*cF*: $ boat-day^{-1})	Reg. 2	526.4 (476.99 : 575.11)	Reg. 5	563.1 (512.04 : 615.42)	
Fuel (*cF*: $ boat-day^{-1})	Reg. 3	526.11 (477 : 576.45)	Reg. 6	760.19 (708.98 : 812.81)	
Incidentals (*cO*: $ boat-day^{-1})		44.26 (22.98 : 65.98)		44.26 (22.98 : 65.98)	44.26
Annual fixed costs:					
Vessel costs (*Wy*: $ boat^{-1})		28637 (23608 : 34769)		46170 (39403 : 53998)	42646
Total investment (*Ky*: $ boat^{-1})		255330 (191910 : 338710)		673590 (551810 : 817980)	589719
Proportion allocated to EKP (ρ)		0.5 (0.4 : 0.6)		0.67 (0.57 : 0.76)	0.63
Revenue from by-product:					
Catch value (*by*: $ boat-day^{-1})	Reg. 1	195.91 (182.15 : 209.65)	Reg. 4	221.89 (86.7 : 349.14)	143
	Reg. 2	211.42 (177.06 : 244.26)	Reg. 5	122.26 (52.08 : 192.01)	
	Reg. 3	112.87 (100.99 : 124.95)	Reg. 6	62.91 (2.73 : 122.84)	
Annual fishing effort:					
Mean number of days boat-year^{-1}		42 (33 : 52)		74 (66 : 83)	68
Annual economic rates:					
Interest rate (*i*)		0.05 (0.034 : 0.072)		0.05 (0.034 : 0.072)	0.05
Opportunity cost (*o*) = *i*					
Depreciation rate (*d*)*		0.02 (0.02 : 0.037)		0.02 (0.02 : 0.037)	0.02

*Uniform variation between lower and upper confidence intervals.

*6.1.6 Reference points and management procedures (for details see 17 Appendix 5. Bioeconomic modelling of the eastern king prawn (*Melicertus plebejus*) fishery)*

Model simulations were used to estimate management reference points and evaluate the proposed management procedures. The simulations were driven by forward projection methodology similar to Richards *et al.* (1998). For driving the simulations, one thousand multivariate length-spatial parameter estimates were created from the MCMC covariance matrix. Bootstrap parameter estimates were used for the delay difference model. For economics, one thousand random variations on Table 6-1 were generated based on each variable's variance. The parameters were used to simulate future realities. The projections were conducted under two conditions: 1) deterministic recruitment to estimate equilibrium maximum sustainable yields (MSY: objective to maximise annual harvest) and maximum economic yields (MEY: objective to maximise Net Present Value for fishing vessels) and 2) stochastic recruitment to evaluate management procedures over 2011 to 2020 in the length-spatial model only.

Several management procedures were developed through a series of meetings with managers, stakeholders and scientists (Table 6-2). They considered one-monthly trawl closures, cap on total fishing effort and within-year catch-rate control-rules. In total 18 scenarios were investigated to assess management over ten years. The following performance measures were used: (i) industry functioning – average annual harvest and effort, (ii) economics – relative net present value (NPV) and average catch rates, and (iii) 2020 population status – spawning egg production and biomass.

Table 6-2. New South Wales and Queensland eastern king prawn management procedures simulated over ten future years in the length-spatial model. Note these were proposed for simulation modelling only and not Fisheries policy.

Management brief	Management procedures Total effort (max boat days)	Regions closed	Month closed (month number)
1. Status quo.	Max last five years, $\sum \approx$ 30000	Qld inshore (area 4)	Oct (12)
2. Close NSW southern and Qld inshore waters in January.	Max last five years, $\sum \approx$ 30000	NSW (area 1) Qld (area 4)	Jan (3)
3. Close Qld waters in January.	Max last five years, $\sum \approx$ 30000	Qld waters (areas 4 to 6)	Jan (3)
4. Close all NSW and Qld waters in January.	Max last five years, $\sum \approx$ 30000	All waters (areas 1 to 6)	Jan (3)
5. Limit total effort to E_{MEY}, and close all waters in January.	$E_{MEY} \approx 9000$	All waters (areas 1 to 6)	Jan (3)
6. Limit total effort to E_{MSY}, and close regional waters on catch rate thresholds.	$E_{MSY} \approx 44000$	Variable m_r to Oct (12)	
7. Limit total effort to E_{MEY} and close regional waters on catch rate thresholds.	$E_{MEY} \approx 9000$	Variable m_r to Oct (12)	

Table footnotes:

A. **Months:** Fishing year months (m) were ordered from 1=Nov to 12=Oct. The time closed Oct (12) ≈ current Qld southern shallow water closure.

B. **Regions:** Areas (*r*) were ordered from south to north, where NSW sth =1, NSW mid = 2, NSW nth = 3, QLD inshore = 4, Qld deep sth = 5, Qld deep nth =6.

C. **Closures m_r:** Calculate adaptive closures for different areas and months (Jan to Oct) based on catch rate thresholds $m_r = \text{firstmonth}\left(cr_{r,m} < cr_{r,.m}^{\text{limit}}\right)+1$, where $cr_{r,m}$ was the standardised catch rate (kgs) for region *r* and month m, $cr_{r,.m}^{\text{limit}}$ was the standardised catch rate reference point, and +1 month provides industry time to prepare for area shut down. The first two months of the fishing year, November and December, were always open.

D. **Fishing effort:** Total effort was split across areas and months based on historical patterns (17.10 Supplementary Material 5: Model projection data). Beta distribution was assumed for implementation error on $E_{\text{status-quo}}$ and E_{MSY} fishing efforts; based on the ratio of 2006-2010 fishing effort to $E_{\text{status-quo}}$. If a region was closed from fishing, a proportion of remaining fishing effort was reallocated to other regions (17.10.2 Fishing effort movement matrix).

E. **Conditions:** The management procedures were simulated over ten future years using a) fixed 2010 fishing costs and power and b) increased fishing costs and power (@ 3% year^{-1}).

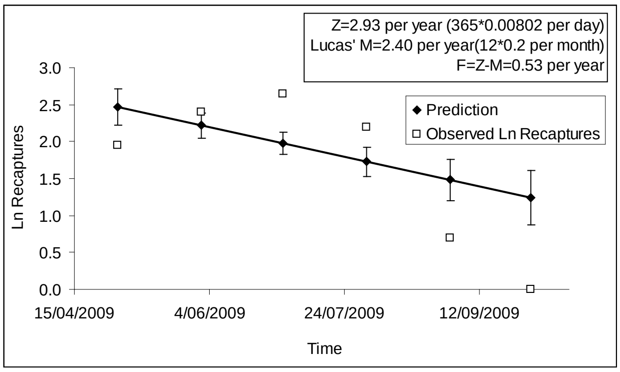
6.1.7 Assessment of the proposed North Reef closure (for details see 18 Appendix 6. Yield and value per recruit assessment of the proposed North Reef closure on eastern king prawns)

In recent years, industry has raised concern over possible growth overfishing of EKP in the northern part of the fishery and identified an area in the vicinity of North Reef (~23^{o}S) for possible closure to address the problem (Figure 6-1). Closing the area would increase the size and age of the prawns at first capture. We used per recruit analyses to assess how the closure might affect catch yield and value.

Prawns from within and around the proposed closure were sampled at 83 sites during the two research charters in 2009 and 2010 to provide information on size and age classes. The ages of the prawns were derived using the inverse von Bertalanffy growth equation:

$$t(L) = t_o - \frac{1}{K} ln(1 - \frac{L}{L_\infty})$$

Tagging data were used to provide estimates of the instantaneous rate of total mortality (*Z*) and fishing mortality (*F*). The resulting estimates of *F* were quite low, 0.26 and 0.53 per year, and indicated that the stock was lightly exploited in this part of the fishery. Yield per recruit is strongly influenced by fishing mortality and in general, closures are only beneficial when the stock is harvested at relatively high exploitation rates.



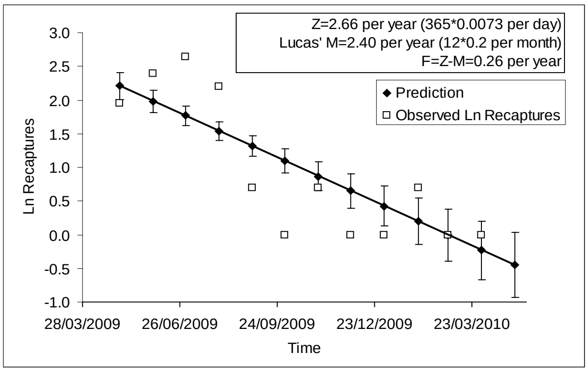


Figure 6-2. Estimates of the instantaneous rates of total mortality (*Z*) and fishing mortality (*F*), based on the decline in recaptured tagged eastern king prawns over six months (left) and 13 months (right) in the northern part of the fishery. The estimates of *F* were considered in per recruit analyses on the effects of closing part of the fishery on yield and value.

7 Results/Discussion

7.1.1 Recruitment dynamics in the northern part of the fishery (for details see 15 Appendix 3. Recruitment dynamics of eastern king prawns in their northern distribution (Objective 1))

The collective results from tagging, prawn sample length-frequency distributions, commercial catch grading data and logbook data strongly suggest that recruitment of EKP in the northern part of the fishery (i.e., 22°–24°S) is largely dependent on prawns migrating off shallow offshore reefs associated with the Capricorn-Bunker Group, rather than from adjacent inshore nursery habitats. This is unusual and has not been reported before for *M. plebejus*, although offshore coral reefs are the juvenile habitat for another closely related species (*Melicertus longistylus*) which is also trawled on the Queensland coast. Logbook data show negligible catches of EKP occur west of the Capricorn-Bunker group, between the islands and the coast, despite significant trawl fishing effort in the area.

While areas around Fraser Island (25°S), including the Great Sandy Straits and the Wide Bay Bar, are important sources of juvenile prawns to the Fraser Island fishery, past and recent tag-recapture results suggest that the number of prawns migrating north of Fraser Island is quite low. As such, Fraser Island and more southern areas, do not appear to contribute significantly to catches further north between 22°S and 24°S. Tagging demonstrated a clear movement of EKP from areas around North Reef eastwards towards the Swain Reefs (Figure 6-1).

The timing of recruitment in the northern part of the fishery, based on analysis of the commercial catch grading data, is consistent with other parts of the fishery. In December-January catch rates of the smallest commercial grade reported (i.e., 21-30 prawns per pound, or 15-22 g) peak in the fishery, while catch rates of next largest size grade (16-20 prawns per pound, or 23-29 g) peak in March.

These temporal and spatial patterns in recruitment should be considered by the fishery managers and stakeholders when attempting to maximise value from the fishery and reduce growth overfishing.

7.1.2 EKP economic survey results (for details see 16 Appendix 4. Economic survey of the eastern king prawn fishery (Objective 2))

An economic analysis of the Queensland eastern king prawn (EKP) trawl fishery is presented based on data obtained from a voluntary economic survey of commercial fishing for the 2007/08 financial year. In total, 24 EKP fishers provided data on their costs, with income estimates derived using logbook for 26 vessels and seafood price data. Following are the key findings. These data were used in the bioeconomic modelling of the fishery.

1. *Average Fixed Cost (AFC)* for a license holder working in the Queensland EKP fishery was $41,323 for the 2007/08 financial year.

2. *Average Variable Cost (AVC)* was $318,849 for 2007/08 financial year.

3. *Average Invested Capital (AIC)* for 2007/08 was $782,264 per license.

4. *Average Depreciation* (includes only primary vessel and electronics) was $25,901 per licence for the 2007/08 financial year.

5. *Average Labour Cost* per license was $148,323 for 2007/08, based on a total of 64 employees reported among the surveyed license holders. The average number of employees per license was 2.7. This labour cost estimate is generally considered to be high, probably because some survey participants included shore-based staff (i.e., office administration and workshop staff) in their reported labour costs.

6. *Average Gross Value of Product (GVP)* was estimated using the Fisheries Queensland logbook data for 26 EKP fishers averaged over a 4-year period (2005-2008 calendar year). Average annual GVP was $378,674. The average annual GVP for the 26 vessels combined was just under $10 million.

7. *Average Boat Gross Margin (BGM)* was $59,825 for 2007/08.

8. *Average Boat Operating Surplus (BOS)* for the 2007/08 financial year was $18,502.

9. *Gross Returns Index (GRI)* for the 2007/08 financial year was 105.14 per license.

10. *Total Vessel Cost (TVC)* was estimated as the sum of the average annual fixed and variable costs, and labour costs, to be $508,495 for 2007/08.

11. *TVC compared to GDP*. When average TVC of $508,495 was subtracted from the average GVP of $378,674, an average annual loss of $129,821 was obtained per license.

The logbook data indicate that the 26 vessels used to estimate GVP land about $10 million of product annually, with about 98% of the catch value attributed to eastern king prawns. Given that the Queensland fishery lands about $30 million annually of EKP, the sample size accounts for about one-third of the fishery's total landings. As there are about 200 vessels operating in the Queensland EKP fishery, the results suggest that the survey participants were probably from more powerful or more efficient vessels, or deployed better skippers, than average license holders. Despite the resulting relatively high average annual GVP of $378,674, the total vessel cost (TVC) still exceeded GVP by $129,821 (i.e., an average loss per license). This is likely due, in part, to the high labour costs (i.e., $148,323 per license) reported by some license holders. If we chose an alternative labour cost estimate, e.g., based on 28% of average GVP (i.e., 0.28 x $378,674), the average labour cost is reduced by about $42,000 to $106,029. While this substantially lowers the labour cost estimate, it is still not enough to prevent TVC from exceeding GVP, hence indicating that for an average license holder, the fishery is not economically viable.

*7.1.3 Bio-economic modelling (for details see 17 Appendix 5. Bioeconomic modelling of the eastern king prawn (*Melicertus plebejus*) fishery)*

The results below are a summary of key outputs and the reader is referred to section 17 for more detailed methods, results and discussion on all model outputs. These results differ slightly from the final model simulations undertaken during the project, which were published in the scientific literature and can be found in section 22. Thus, while more detailed descriptions of the methods are presented below and in section 17, the reader is directed to section 22 for the most recent model outputs and estimates of key fishery reference points for the fishery. It should be noted that all model results were dependent on the validity of the logbook EKP harvest and standardised catch rates.

Stock status

The length-spatial model predicted that historical EKP spawning egg production and exploitable biomass, expressed as a median ratio relative to 1958, declined roughly 40–50% up to 1985 and remained steady to 2006 (Figure 7-1). The median ratios have increased since 2006 to 60–80% of 1958 levels.

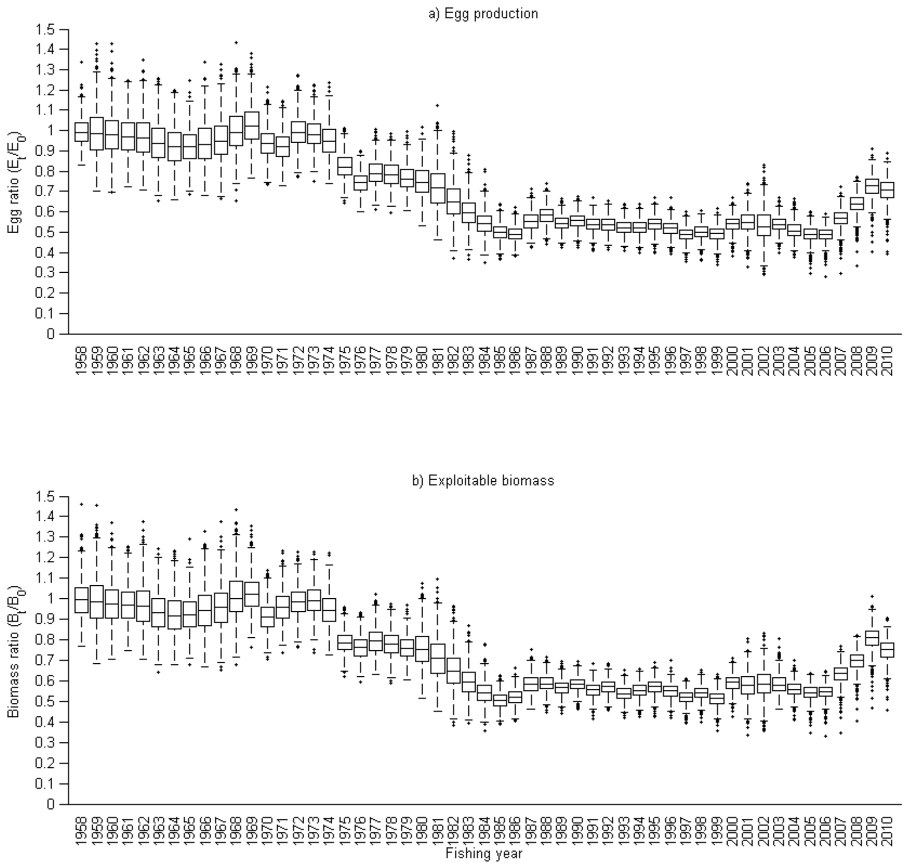


Figure 7-1. Box-plots of estimated yearly change in eastern king prawn a) egg production and b) exploitable biomass from the length-spatial model. The plots display the simulated distributions (1000 samples; expressed as a ratio of virgin eggs E_0 and biomass B_0) around their medians (line in the middle of each box). The tops and bottoms of each "box" are the 25th and 75th percentiles respectively. Ratios beyond the whisker length (≈2.7σ) are marked as low probability estimates.

Delay difference models 1 and 2 predicted historical EKP exploitable biomass ratios at a low of about 40% in 1985, then varied around 50–60% to 2006, and increased to about 75% in 2010 (Figure 7-2).

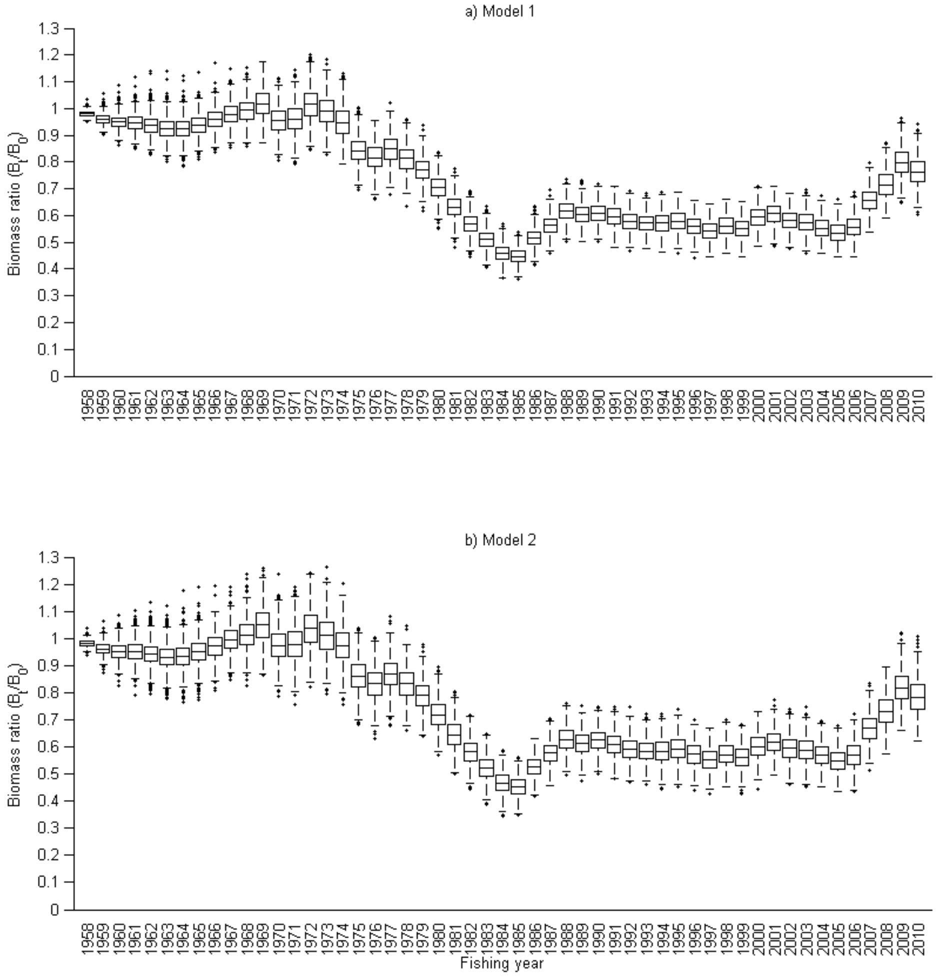


Figure 7-2. Box-plots of estimated yearly change in eastern king prawn exploitable biomass from a) delay difference model 1 with fixed M=0.18 and b) delay difference model 2 with estimated M=0.21. The plots display the simulated distributions (1000 samples; expressed as a ratio of virgin biomass B_0) around their medians (line in the middle of each box).

Maximum sustainable and economic yields

The calculation of reference points for MSY and MEY were based on optimising the population and economic models through fishing mortality ($\propto$ fishing effort). The results were dependent on the specified conditions, and particularly influenced by the assumed monthly pattern of fishing, level of fishing power and economic parameters.

It should also be noted that the fishing pattern for the base case of MEY calculation retained the current number of days fished per vessel ($\bar{d}$). A higher value of MEY was obtained when the number of days per vessel was allowed to increase (case $2\bar{d}$).

In total ten MSY and MEY optimisation groups (Opt) were conducted with the length-spatial model (five combinations of effort patterns by two economic conditions). Delay difference model MSY and MEY were estimated only for status quo management (Opt 1). This model used fixed "States combined" average economics. The results from all model runs were described in 17 Appendix 5. Bioeconomic modelling of the eastern king prawn (*Melicertus plebejus*) fishery. Error bar widths should be considered along with the mean results.

From the length-spatial model:

- MSY was about 3100t. E_{MSY} was about 38,000 boat-days under 2010 average vessel fishing power and about 28,000 boat-days if fishing power continued to increase 3% p.a. over the next decade.
- E_{MEY} was about 7000 boat-days under $\bar{d}$ for current (i.e., 2010) fishing power MEY was about 1300 t.
- E_{MEY} was about 13,000 boat-days under $2\bar{d}$, and 10,000 boat-days for higher fishing power. MEY was about 2000 t.

From the delay difference model ($\bar{d}$):

- MSY was about 2900 t and E_{MSY} 27,000 boat days.
- MEY was about 2300 t and E_{MEY} 14,000 boat days

Mean catch rate reference points, corresponding to MSY and MEY, were derived for simulating within year monitoring and management of the EKP fishery (length spatial model). The MSY catch rate indices corresponded to a breakeven point for mean vessel profitability and lower EKP abundance than MEY. The MEY catch rate indices represented two forms: i) EKP catch rates that maximised fishing profit against variable costs (no fixed costs; labelled as MEY_v), and ii) EKP catch rates that maximised fishing profit against variable costs plus fixed costs (labelled as MEY_{vf}; defined by $\bar{d}$). These mean reference points were compared retrospectively against historical standardised catch rates (Figure 7-3). Regionally, the catch rate reference points suggested:

- Consistent profitable catch rates in the last three years across all regions,
- Region 2 catch rates were highly variable to compare against the mean reference points.
- Region 4 catch rates were barely profitable between 1988 and 2006.
- Region 5 catch rates were profitable over all years.
- Regions 1, 3 and 6 catch rates were typically profitable with some marginal years.

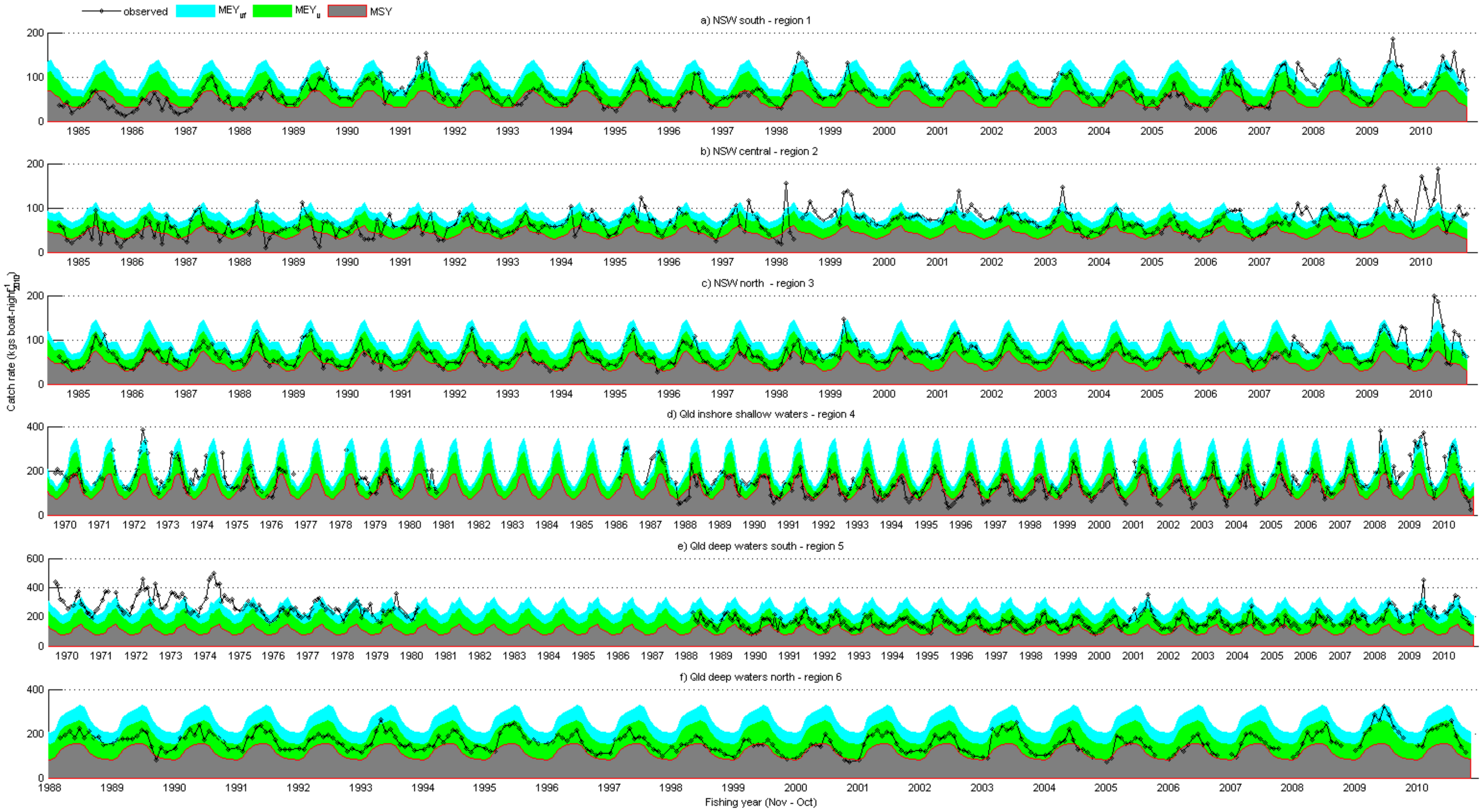


Figure 7-3. Retrospective comparison of standardised catch rates against catch rate reference points.

Harvest strategy evaluations
A number of EKP fishery management procedures were evaluated over 10 future years using the length-spatial operating model (Table 17-12). Management procedures 1 to 4 represented status quo total fishing effort and compared alternate one-month regional EKP closures. Procedure 5 contrasted procedure 4 with reduced total fishing effort at E_{MEY}. Procedures 6 and 7 used regional catch rate control rules (MSY or MEY for variable costs) to manage total fishing efforts of E_{MSY} and E_{MEY} respectively. The management procedures were replicated in two scenarios groups: i) 1 to 7 under 2010 fishing costs and fishing power, and ii) 8 to 14 under 3% p.a. increase to both costs and fishing power. Each scenario was evaluated using six performance measures representing industry functioning, economic conditions, and population change. For management procedures 6 and 7, probabilities of catch rates closing fishing regions were calculated. The EKP median results were summarised as follows (see box plots in section 17 Appendix 5. Bioeconomic modelling of the eastern king prawn (*Melicertus plebejus*) fishery):

Management procedures 1 to 4 ($E_{status\text{-}quo}$ ≈ maximum 30,000 boat-days)

- There were no significant changes in EKP performance measures, except Net-Present-Value (NPV) scenarios declined in order of 20% with increasing fishing costs.
- Expected annual harvests were about 3000 t taken at 110 kg boat-day^{-1}.
- Management via altering regional monthly closures, with status quo fishing effort, resulted in no EKP spawning or biomass increase.

Management procedure 5 (E_{MEY} ≈ 9000 boat-days)

- Compared to procedures 1 to 4, there were 40-50% significant increases in NPV, catch rates, spawning and biomass.
- Expected annual harvests were halved at about 1550t from 9000 boat-days. However, catch rates were high at about 160-170 kg boat-day^{-1}.
- NPV was reduced by increased costs, but still in order of 40% above procedures 1 to 4.
- Management via reduced fishing effort resulted in larger profit but reduced total harvest.

Management procedure 6 (E_{MSY} ≈ 44,000 boat-days and $CPUE_{MSY}$ control rules)

- Compared to procedures 1 to 4, there were no significant changes in EKP performance measures.
- Annual harvests and fishing efforts were highly variable.
- The probability of closing fishing regions after April (≈ 6 months) was high. The region 4 closure probability was 60% after February. Increasing fishing costs and power did not significantly change the closure probabilities.
- Management via MSY fishing effort and MSY catch rates maintained the EKP population status by reducing the fishing year (≈ June to October closure).

Management procedure 6 (E_{MSY} ≈ 44,000 boat-days and $CPUE_{MEYv}$ control rules)

- Compared to procedures 1 to 4 and 6-$CPUE_{MSY}$, there were significant reductions in total fishing harvest and effort. However, NPV, catch rates, spawning and biomass levels were about 30% higher.

- Expected annual harvest was 1950 t, and total effort was managed at about 16,000 boat-days.
- The probability of closing fishing regions after February (≈ 4 months) was high.
- Management via MSY fishing effort and MEY_v catch rates maintained a higher EKP population status by reducing the fishing year (≈ March to October closure).

Management procedure 7 (E_{MEY} ≈ 9000 boat-days and $CPUE_{MSY}$ control rules)

- Results were similar to management procedure 5, with 40-50% significant increases in NPV, catch rates, spawning and biomass.
- Expected annual harvests were halved at about 1550 t from 9000 boat-days. Catch rates were in order of about 160-170 kg boat-day^{-1}.
- The probabilities of regional closures were significantly less compared to procedure 6-$CPUE_{MSY}$. Regions 1, 2 and 4 had about a 20% chance of closure after June. The probabilities were less than about 5% for regions 3, 5 and 6.
- Management via MEY fishing effort and MSY catch rates maintained higher and more profitable EKP population status.

Management procedure 7 (E_{MEY} ≈ 9000 boat-days and $CPUE_{MEYv}$ control rules; Figure 17-15, Figure 17-16b and d)

- The results were similar to management procedure 5.
- This procedure resulted in the highest catch rates, spawning and biomass.
- Expected annual harvests were lowest at 1250 t and effort at 6500 boat-days.
- The closure probabilities were significantly higher from March to October; marginally lower for regions 5 and 6.
- Management via MEY fishing effort and MEY_v catch rates maintained a higher EKP population status by reducing the fishing year (≈ March to October closure).

Simulation of EKP fishery dynamics and management procedures identified spawning egg production (S) and exploitable biomass (B) ratios were above reference limits of 50% S_{MSY} and 40% B_{MSY}. MSY was estimated in the range between 2800 t and 3200 t. Fishing effort E_{MSY} was uncertain ranging from 44,000 down to 27,000 boat-days depending on model selection, within-year regional fishing patterns and assumed fishing power. Assuming continued static management roughly every decade and strong change in fishing power, E_{MSY} should be considered in the range 27,000 to 32,000 boat days per year. The uncertainty surrounding the value of E_{MSY} was not unusual for a fisheries stock assessment. The result confirmed that target fishing efforts should not approach these limits under consideration of higher risks of over fishing and lower profitable catch rates.

EKP MEY estimates were strongly influenced by the reported high costs (variable and fixed) of fishing, the assumed average number of days fished per vessel year ($\bar{d}$) and fishing power. The MEY ranged between 1400 t and 2100 t and E_{MEY} between 9000 and 14,000 boat-days. The interaction between cost parameters and fishing power was intricate, but suggested less than 175 vessels (for the NSW and Qld fishing fleets combined) were required for MEY; assuming $\bar{d}$. Higher $\bar{d}$ significantly increased profit, but reduced the optimal number of vessels.

As typically found, the estimates of MEY were substantially less than MSY. The higher fishing costs and/or lower product prices decrease the ratio of MEY to MSY. The EKP ratio of MEY to MSY, assuming $\bar{d}$, was surprising low. This was due to the high costs, particularly the annual fixed costs. For a States-combined average vessel, about 83 kg boat-day^{-1} of EKP was required to cover variable (on-water) fishing costs only. This increased dramatically to 154 kg boat-day^{-1} in order to cover both variable and fixed costs; this was 118 kg boat-day^{-1} assuming $2\bar{d}$. These calculated catch rates for approximate breakeven cost–profit illustrate the sensitive nature of assumptions and equations used to estimate MEY.

Of the EKP simulations, management procedure 7 using E_{MEY} and $CPUE_{MSY}$ performed the best; followed closely by management procedure 5. EKP fleet profit, catch rates, spawning egg production and biomass were all significantly higher than status quo. They were robust under future increases in fishing costs and power. Catch rate control rules were effective under E_{MEY}, but less so under high E_{MSY}, where the control rules successfully reduced effort but caused uncertain harvest and high probability of closing fishing regions mid-year. This unwanted management performance was corrected under E_{MEY}. $CPUE_{MSY}$ was an appropriate trigger point given catch rate observation uncertainties. Under higher fishing effort, the baseline settings of the catch rate trigger ($CPUE_{trigger}$) were more critical. If kept at $CPUE_{MSY}$ or less, higher fishing effort would not be correctly constrained. If the catch rate trigger was increased to towards $CPUE_{MEYv}$, effort management improved but at the cost of shorter fishing seasons. The setting of the $CPUE_{trigger}$ required balancing historical knowledge of the fishery, where and when EKP were abundant and data/opinion on profitable catch rates. This catch rate control rule was dependent on up-to-date electronic data collation of each vessel's daily catch rates and fishing power variables. Modernisation of onboard catch reporting data systems should be of high priority to improve data quality and completeness, and reduce administration time and costs.

The State Governments manage each of their respective EKP sectors independently through a range of input controls. In 2010 about 600 vessels were licensed to fish EKP. Between 2006 and 2010 about 350 vessels were active and fished 20,000 to 30,000 boat-days per year. Analysis of these vessel and effort numbers produced suboptimal profit for the fleet as a whole. Simulations demonstrated that reduced vessel numbers and fishing effort were the most effective management changes to improve fleet profit. Even so, these controls alone may not always be a safeguard against unpredictable situations or issues. Monitoring regional changes in fishing effort should be done carefully given hyperstability bias caused by temporal changes in fishing power (catchability) and where and how vessels fished. Seasonal patterns in latent fishing effort should be minimised. Analysis showed that the one-monthly spatial/seasonal closures were not important. However, the estimated seasonal patterns of fishing suggested more focus on larger prawns over the autumn and winter months than late spring and summer. Spatial/seasonal closures should still be considered for reasons of improving future profit, reducing risk of overfishing, industry downtime and minimising capture of small prawns.

This research has described a new assessment model and evaluated more profitable management procedures for the eastern king prawn fishery. It has also described the conditions to set within-year catch-rate harvest control rules. All the management procedures evaluated were simple to follow and directly adaptable for new EKP management. Financial conditions are currently difficult for industry and government alike. This should not prevent new management decisions. If future finances limit EKP monitoring accuracy, then more precautionary interpretation of results should be considered. This would be due to increased uncertainty of sustainable and profitable fishing resulting from fewer available data. The EKP stock was assessed as healthy in 2010. However, the key management change for increased fishery profit was to reduce fishing effort to between 9000 and 20,000 boat-days per year over New South Wales and Queensland waters. The actual value to set will depend on considerations of model uncertainties and government/industry positions. If the current costs of fishing remain steady or increase, fishing effort above 20,000 boat-days will be less profitable. The research has provided evidence for a combined-States monitoring-assessment-management approach for EKP. The State Governments and industry should establish a formal multi-jurisdictional management framework and enhance multiagency stock assessment for EKP. The joint framework would save and share financial resources. It would also better inform stakeholders and the public on management's triple bottom line of economic, ecological, and social success.

7.1.4 Assessment of the proposed North Reef closure (for details see 18 Appendix 6. Yield and value per recruit assessment of the proposed North Reef closure on eastern king prawns

From the length-frequency samples, the modal age of prawns inside the proposed closure was estimated to be 0.5–1.0 years. This range in ages is at, or close to, the ages at first capture required to maximise value (Figure 7-4). Closing the area would increase the age at first capture to about 0.75–1.25 years, resulting in a reduction in catch yield and value. Given that there is no apparent benefit from the closure and that it would likely result in a reduction in catch value, we recommend that it not be implemented. While the per recruit analyses were undertaken for a wide range of fishing mortality rates (*F*), the recapture rates of tagged prawns in the region indicate that fishing mortality is likely to be low – estimated to range between 0.26 and 0.53 per year.

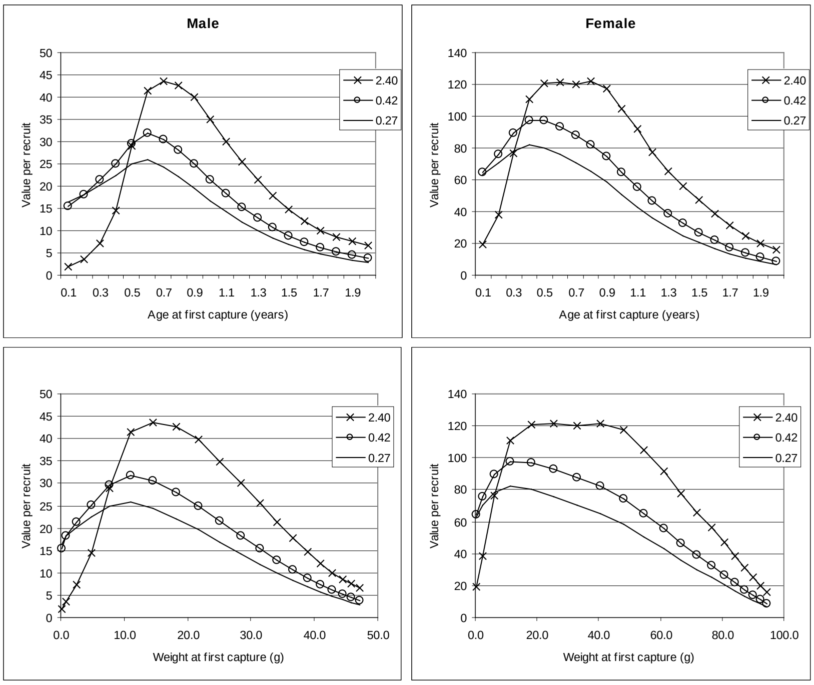


Figure 7-4. Value per recruit for male and female eastern king prawns, at three fishing mortality rates. Note higher value per recruit would be achieved at a higher fishing mortality rate than that currently applied in this part of the fishery.

8 Benefits and adoption

The main beneficiaries of the study are eastern king prawn fishers in Queensland and New South Wales, fish processing operators involved in the marketing of EKP, and fishery managers in both states.

The project evaluated 18 management scenarios that were put forward by fishers and managers. These included one-monthly trawl closures, a cap on total fishing effort, and within-year catch rate control rules. They also considered assumptions about future operating costs and changes in fishing power. The study found that a) the number of vessels operating in the fishery needed to be reduced to secure more profitable fishing, b) alternative one-month closures did little to improve profitability, and c) catch rate reference points were effective for monitoring and management, but not with excess effort.

Results from per recruit analysis of the proposed North Reef closure were considered by industry and were influential in industry deciding not to implement the closure.

The results were presented to industry and other stakeholders during the project steering committee meetings and further presentations are planned. Adoption of the main findings pertaining to MSY and MEY are contingent upon industry acceptance in both states. The results have influenced Fisheries Queensland preparations for consulting industry and the public about the future Queensland Trawl Fishery Management Plan. This is planned to be undertaken via a publicly-released Regulatory Impact Statement.

9 Further development

The EKP fishery is a commercially valuable stock in Queensland and New South Wales, as well as fished recreationally in New South Wales coastal lakes. An important outcome of the project was annual project steering committee meetings of commercial fishers, managers, scientists and economists from both states with a common interest in improving research and management of the fishery. It would be a significant achievement if this collaboration was maintained indefinitely. Such an initiative might also reduce research and management costs, by sharing tasks such as updating fishing power changes and the collection of economic data. The committee could be called "*The Joint Queensland and New South Wales Collaborative Committee for Research and Management of the Eastern King Prawn Fishery*" and would ideally be funded by industry and government from both states.

Results from the tagging, length-frequency, logbook and commercial catch grading datasets all support the hypothesis that EKP in the northern distribution of the fishery recruit from the offshore Capricorn-Bunker Island group. This hypothesis could be further validated with a dedicated juvenile prawn sampling program on the intertidal reef flats of the islands in the region. There does not appear to be any published reports of EKP utilising such habitats, although another closely related species, the red spot king prawn *M. longistylus*, is restricted to reefs during its juvenile phase.

If the fishery management objectives include economic targets, such as MEY and E_{MEY} reference points, then ongoing collection of economic data is required. This could be jointly funded by industry and government. Similar annual or biannual trawl fishery economic data collection initiatives are conducted by the Northern Prawn Fishery Industry and ABARES for the NPF, and by Econosearch (2009) for South Australia's prawn fisheries. Our economic survey data were based on relatively few fishers. Ideally, a purposely-designed detailed annual face-to-face survey seeking input from the whole fleet (i.e., Queensland New South

Wales) would result in the most comprehensive and reliable data. Alternatively, data could be obtained by including survey questions as part of the logbook program. While the latter option may be cheaper, it would also likely result in lower quality data.

Further discussion and development of the economic parameters used to derive net present value (NPV) are required, including rules for determining which fixed and variable costs to include. An improved definition of labour costs would be productive. The labour cost estimates based on the survey data were deemed to be too high, possibly because some interviewees included land-based staff labour costs. We ended up using a simple fixed proportion (i.e., 0.29) of catch value as labour costs. Discussion about the most appropriate size of vessels (i.e., standardised hull unit or fishing power) and the number of days fished per vessel is needed. We considered scenarios that included the average number of days fished per boat ($\bar{d}$) and twice this ($2\bar{d}$). These discussions are needed to estimate the number of vessels required to achieve MEY and E_{MEY}.

We used a deterministic monthly migration pattern to model the movements of prawns between the six regions. Modelling of stock could be improved by incorporating uncertainty in the movement matrix between years.

10 Planned outcomes

The project outputs have contributed directly to planned outcomes. New methodology was developed for stock assessment, calculation of model-based and data-based reference points and management strategy evaluation of the fishery throughout its distribution in Queensland and New South Wales. Outcomes include presentations of stock assessment and harvest strategy evaluations to industry, managers and other stakeholders from both states. Results from 18 management scenario evaluations were presented. Project outputs have been considered by fishery managers in both states and at the time of writing were being considered in revision of the Queensland Trawl Fishery Management Plan.

Eastern king prawns are the first Queensland commercial fishery to have a quantitative estimate of MEY and E_{MEY} derived for consideration by fishers and management.

The project evaluated the effects of spatial and temporal closures, and provided advice to fishers and managers, who are now in a more informed position to make decisions pertaining to closures.

The project's effort to inform stakeholders and disseminate information, which contributes directly to the planned outcomes, is reflected in the following industry and scientific publications:

1. Prosser, A. and Courtney, A. J. (2008) EKPs to be tagged in Fraser-Swains area next month. *Queensland Fisherman* 26 (12): 20.

2. Courtney, A. J. and Prosser, A. (2009) Research update on the eastern king prawn fishery. *Queensland Fisherman* 27 (10): 20-23.

3. Braccini, J. M., O'Neill, M. F., Campbell, A. B., Leigh, G. M. and A. J. Courtney (2012). Fishing power and standardised catch rates: Implications of missing vessel-characteristic data from the Australian eastern king prawn fishery. *Canadian Journal of Fisheries and Aquatic Sciences* 69, 797-809.

4. Braccini, J. M., O'Neill, M. F., Courtney, A. J., Leigh, G. M., Campbell, A. B., Montgomery, S. S. and A. J. Prosser (2012) Quantifying northward movement rates of eastern king prawns along eastern Australia. *Marine Biology* DOI: 10.1007/s00227-012-1983-9

5. Lloyd-Jones, L. R., Wang, Y-G., Courtney, A. J., Prosser, A. J. and S. S. Montgomery (2012). Latitudinal and seasonal effects on growth of the Australian eastern king prawn (*Melicertus plebejus*). *Canadian Journal of Fisheries and Aquatic Sciences* 69:1525-1538. DOI:10.1139/f2012-072

6. Braccini, J. M., Campbell, A. B., Courtney, A. J., Die, D. J., Prosser, A. J. and Montgomery, S. S. (2013). Stochastic growth analysis of eastern king prawns *Melicertus plebejus*. *Crustaceana* 86(6):651-660

7. O'Neill, M. F., Leigh, G. M., Wang, Y.-G., Braccini, J. M. and Ives, M. C. (2014). Linking spatial stock dynamics and economics: evaluation of indicators and fishery management for the travelling eastern king prawn (*Melicertus plebejus*) *ICES Journal of Marine Science; doi:10.1093/icesjms/fst218*

11 Conclusion

Objective 1. *Investigate the recruitment dynamics of eastern king prawns in their northern-most distribution (i.e., the North Reef-Swain Reefs area).*

This objective has been achieved. We used prawn length-frequency data from 83 sampled sites in 2009 and 2010 to infer patterns in the growth, movements and the origin of prawns in this area. We released 3766 tagged prawns, and with support from industry, collected information on movements and growth from the recaptures over the following two years. We also examined a large daily catch grading dataset, comprised of about 2000 t over 10 years from five vessels, to infer patterns in recruitment. We also examined temporal and spatial trends in logbook data. Collectively, the analyses provided a clearer understanding of the recruitment dynamics of prawns in the northern part of the fishery, which is located over 100 km from the coast. The prawns appear to utilise offshore reefs associated with the Capricorn-Bunker Island group as nursery grounds, and migrate east-northeast towards the Swain Reefs. The findings were used to evaluate an industry-proposed closure in the area.

Objective 2. *Undertake an economic analysis of the eastern king prawn fishery and determine the optimum yield and effort for profitability.*

This objective has been achieved. The project utilised an economic survey that was developed by Fisheries Queensland to obtain data from EKP fishers for the 2007/08 financial year. Estimates of average fixed and variable costs, invested capital, depreciation, labour costs and gross value of product were obtained. Average total vessel costs exceeded average gross value of product, indicating that most EKP fishers made a loss in 2007/08. This was partly due to high labour costs reported by some interviewees, which included labour costs for land-based employees. The economic data were used in the bioeconomic modelling of the fishery.

Objective 3. Develop (computer) models of the eastern king prawn fishery that evaluate alternative harvest strategies, as identified by the fishery managers and fishers, and provide *advice on the efficacy of each strategy in achieving biological and economic management objectives.*

This objective has been achieved. New methodology was developed for stock assessment, calculation of model-based and data-based reference points and management strategy evaluation for the whole (i.e., Queensland and New South Wales) EKP fishery. Bioeconomic fishing data were standardised for calibrating a new length-spatial structured operating model. Results were compared against a standard delay difference biomass model. Eighteen management scenarios were evaluated, which included assumptions pertaining to increasing operational costs and increases in fishing power. Simulations identified that a) boat numbers had to be reduced to secure more profitable fishing and reduce the risks of overfishing, b) alternative one-month spatial closures did little to improve profitability, and c) catch rate reference points were effective for monitoring and management, but not with excessive fishing effort. If current fishing costs remain steady or increase, fishing effort levels between 9000 and 20000 boat-days per year will produce higher profit. Decision makers need to consider the uncertainty, assumptions and political views affecting economic yields. The results have been presented to managers and scientists from both states, and some Queensland industry representatives. Further presentations of the results are planned.

12 References

ABARES (2011) Agricultural commodity statistics 2011. (Ed. FaF Department of Agriculture). (Australian Government)

Australian Government (2007) Commonwealth Fisheries Harvest Strategy: Policy and Guidelines. (Ed. FaF Department of Agriculture) pp. 55. (Canberra, Australia)

Beverton, R.J.H., and Holt, S.J. (1957) 'On the dynamics of exploited fish populations.' Fisheries Investment Series 2 edn. (UK Ministry of Agriculture and Fisheries: London) 533

Bishop, J., Venables, W.N., Dichmont, C.M., and Sterling, D.J. (2008) Standardizing catch rates: is logbook information by itself enough? *ICES Journal of Marine Science* **65**(2), 255-266. [In English]

Bishop, J., Venables, W.N., and Wang, Y.G. (2004) Analysing commercial catch and effort data from a penaeid trawl fishery - A comparison of linear models, mixed models, and generalised estimating equations approaches. *Fisheries Research* **70**(2-3), 179-193.

Braccini, J.M., O'Neill, M.F., Campbell, A.B., Leigh, G.M., and Courtney, A.J. (2012a) Fishing power and standardized catch rates: implications of missing vessel-characteristic data from the Australian eastern king prawn (Melicertus plebejus) fishery. *Canadian Journal of Fisheries and Aquatic Sciences* **69**, 797-809.

Braccini, M., O'Neill, M.F., Courtney, A.J., Leigh, G.M., Campbell, A.B., Montgomery, S.S., and Prosser, A.J. (2012b) Quantifying northward movement rates of eastern king prawns along eastern Australia. *Marine Biology* **159**(10), 2127-2136.

Broadhurst, M.K., Millar, R.B., Kennelly, S.J., Macbeth, W.G., Young, D.J., and Gray, C.A. (2004) Selectivity of conventional diamond- and novel square-mesh codends in an Australian estuarine penaeid-trawl fishery. *Fisheries Research* **67**(2), 183-194.

Bromley, D.W. (2009) Abdicating Responsibility: The Deceits of Fisheries Policy. *Fisheries* **34**(6), 280-290. [In English]

Campbell, R.A. (2004) CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. *Fisheries Research* **70**(2-3), 209-227.

Carruthers, T.R., Ahrens, R.N.M., McAllister, M.K., and Walters, C.J. (2011) Integrating imputation and standardization of catch rate data in the calculation of relative abundance indices. *Fisheries Research (Amsterdam)* **109**(1), 157-167. [In English]

Carruthers, T.R., McAllister, M.K., and Ahrens, R. (2010) Simulating spatial dynamics to evaluate methods of deriving abundance indices for tropical tunas. *Canadian Journal of Fisheries and Aquatic Sciences* **67**, 1409-1427.

Christensen, V. (2010) MEY = MSY. *Fish and Fisheries* **11**(1), 105-110. [In English]

Clarke, K.R., and Warwick, R.M. (1994) 'Change in Marine Communities: An Approach to Statistical Analysis and Interpretation.' (Plymouth Marine Laboratories: Plymouth) 144

Courtney, A.J. (1997) Spawning stock dynamics of penaeid prawns in southeast Queensland and considerations for preventing recruitment overfishing. PhD Thesis, University of Queensland,

Courtney, A.J., Campbell, M.J., Roy, D.P., Tonks, M.L., Chilcott, K.E., and Kyne, P.M. (2008) Round scallops and square-meshes: a comparison of four codend types on the catch rates of target species and bycatch in the Queensland (Australia) saucer scallop (*Amusium balloti*) trawl fishery. *Marine and Freshwater Research* **59**, 849–864.

Courtney, A.J., Cosgrove, M.G., Mayer, D., and Vance, D.J. (2002) 'Developing indicators of recruitment and effective spawner stock levels in eastern king prawns (Penaeus plebejus).' (Department of Primary Industries)

Courtney, A.J., Die, D.J., and McGilvray, J.G. (1996) Lunar periodicity in catch rate and reproductive condition of adult eastern king prawns, Penaeus plebejus, in coastal waters of south-eastern Queensland, Australia. *Marine and Freshwater Research* **47**(1), 67-76.

Courtney, A.J., and Dredge, M.C.L. (1988) Female reproductive biology and spawning periodicity of two species of king prawns, Penaeus longistylus Kubo and Penaeus latisulcatus Kishinouye, from Queensland's east coast fishery. *Australian Journal of Marine and Freshwater Research* **39**(6), 729-41.

Courtney, A.J., Kienzle, M., Pascoe, S., O'Neill, M.F., Leigh, G.M., Wang, Y.-G., Innes, J., Landers, M., Braccini, J.M., Prosser, A.J., Baxter, P., Sterling, D.J., and Larkin, J. (2012) Harvest strategy evaluations and co-management for the Moreton Bay Trawl Fishery. Australian Seafood CRC Project 2009/774. Department of Agriculture, Fisheries and Forestry, Queensland, Brisbane.

Courtney, A.J., Masel, J.M., and Die, D.J. (1995) Temporal and spatial patterns in recruitment of three penaeid prawns in Moreton Bay, Queensland, Australia. *Estuarine, Coastal and Shelf Science* **41**, 377-392.

Cunningham, S., and Whitmarsh, D. (1980) Fishing effort and fisheries policy. *Marine Policy* **4**(4), 309-316.

Dichmont, C.M., Die, D., Punt, A.E., Venables, W., Bishop, J., Deng, A., and Dell, Q. (2001) Risk analysis and sustainability indicators for prawn stocks in the Northern Prawn Fishery. CSIRO Marine Research, Cleveland. FRDC 98/109.

Dichmont, C.M., Pascoe, S., Jebreen, E., Pears, R., Brooks, K., and Perez, P. (2013) Choosing a fishery's governance structure using data poor methods. *Marine Policy* **37**(0), 123-131.

Dichmont, C.M., Pascoe, S., Kompas, T., Punt, A.E., and Deng, R. (2010) On implementing maximum economic yield in commercial fisheries. *Proceedings of the National Academy of Sciences of the United States of America* **107**(1), 16-21. [In English]

Die, D.J., Courtney, A.J., and Cosgrove, M.G. (1999) Effects of Trawl Fishing Closures on Yield and Ex-Vessel Value on the Wide Bay Bar Eastern King Prawn Fishery. Department of Primary Industries, Queensland, No. QI99059, Brisbane.

Dixon, C., and Sloan, S. (2007) Management Plan for the South Australian Spencer Gulf Prawn Fishery. Vol. Paper No. 54, South Australian Fisheries Management Series. (Ed. PIaR SA) pp. 55. (Government of South Australia)

Do Thi Thanh, H., Wang, T., Bayley, M., and Nguyen Thanh, P. (2010) Osmoregulation, growth and moulting cycles of the giant freshwater prawn (*Macrobrachium rosenbergii*) at different salinities. *Aquaculture Research* **41**, 135–143.

Dredge, M., and Gardiner, P. (1984) Survey discovers new central Queensland prawning grounds. *Australian Fisheries* **43**(1), 16-19.

Dredge, M.C.L. (1990) Movement, growth and natural mortality rate of the red spot king prawn, *Penaeus longistylus* Kubo, from the Great Barrier Reef lagoon. *Australian Journal of Marine and Freshwater Research* **41**, 399-410.

Econsearch (2009) Economic indicators for the Spencer Gulf and West Coast Prawn Fisheries 2007/2009. Primary Industries and Resources South Australia.

Fisheries Queensland (2007) Fisheries Long Term Monitoring Program Sampling Protocol – Eastern King Prawn: (2007 onwards) Sections 1 and 2. (Ed. Q Department of Primary Industries and Fisheries, Brisbane, Australia).

Fisheries Queensland (2013) Stock status of Queensland's fisheries resources 2012. Department of Agriculture, Fisheries and Forestry. State of Queensland. .

Francis, R. (2011) Data weighting in statistical fisheries stock assessment models (vol 68, pg 1124, 2011). *Canadian Journal of Fisheries and Aquatic Sciences* **68**(12), 2228-2228.

Garcia, S., and Le Reste, L. (1981) Life cycles, dynamics, exploitation and management of coastal penaeid shrimp stocks. *FAO Fisheries Technical Paper* **203**, 1-215.

Garcia, S.M., and Staples, D.J. (2000) Sustainability reference systems and indicators for responsible marine capture fisheries: a review of concepts and elements for a set of guidelines. *Marine and Freshwater Research* **51**(5), 385-426. [In English]

Gelman, A., Carlin, J.B., Stern, H.S., and Rubin, D.B. (2004) 'Bayesian Data Analysis.' 2nd edn. (Chapman & Hall/CRC)

GenStat (2011) GenStat Fourteenth Edition. 14 edn. (Laws Agricultural Trust.)

Gibbons, R.D., Hedeker, D., and DuToit, S. (2010) Advances in analysis of longitudinal data. *Annu. Rev. Clin. Psycho.* **6**, 79–107.

Glaister, J.P., Lau, T., and McDonall, V.C. (1987) Growth and migration of tagged eastern Australian king prawns, *Penaeus plebejus* Hess. *Australian Journal of Marine and Freshwater Research* **38**, 225-242.

Glaister, J.P., Montgomery, S.S., and McDonall, V.C. (1990) Yield-per-recruit analysis of eastern king prawns, *Penaeus plebejus* Hess, in eastern Australia. *Australian Journal of Marine and Freshwater Research* **41**, 175-197.

Goñi, R., Alvarez, F., and Adlerstein, S. (1999) Application of generalized linear modeling to catch rate analysis of Western Mediterranean fisheries: the Castellon trawl fleet as a case study. *Fisheries Research* **42**(3), 291-302.

Gordon, G.N.G., Andrew, N.L., and Montgomery, S.S. (1995) Deterministic compartment model for the eastern king prawn (Penaus plebejus) fishery in New South Wales. *Marine and Freshwater Research* **46**(5), 793-807.

Grafton, R.Q., Kompas, T., and Hilborn, R.W. (2007) Economics of overexploitation revisited. *Science* **318**(5856), 1601-1601. [In English]

Haddon, M. (2001) 'Modelling and quantitative methods in fisheries.' (Chapman and Hall/CRC: Boca Raton, Florida, U.S.) 405

Hall, N.G., and Watson, R.A. (2000) A spatial representation of the tiger prawn (*Penaeus esculentus*) fishery in Shark Bay, Western Australia. In Fish Movement and Migration. (Eds. DA Hancock, DC Smith and JD Koehn) pp. 212-230. (Australian Society for Fish Biology: Albury)

Haywood, M.D.E., and Die, D. (1997) Assessment of the Torres Strait mackerel fishery - final report. CSIRO Report MR-C 96/12.

Hilborn, R. (1990) Determination of fish movement patterns from tag recoveries using maximum likelihood estimators. *Canadian Journal of Fisheries and Aquatic Sciences* **47**, 635-643.

Hilborn, R. The dark side of reference points. 2002, pp. 403-408

Hilborn, R., and Walters, C.J. (1992) 'Quantitative fisheries stock assessment: choice, dynamics and uncertainty.' (Chapman &Hall: New York)

Horn, P.L. (2003) CPUE from commercial fisheries for ling (Genypterus balcodes) around the North Island, New Zealand: an evaluation of series for LIN 1, LIN 2, and Cook Strait. No. NZ Fisheries Association Report No. 2003/13, Wellington.

Ives, M.C. (2007) Prawns, climate change, rising costs and falling prices: Managing NSW's prawn stocks in a world of uncertainties. A quantitative analysis of prawn harvesting strategies. University of New South Wales, Australia,

Ives, M.C., and Scandol, J.P. (2007) A Bayesian analysis of NSW eastern king prawn stocks (Melicertus plebejus) using multiple model structures. *Fisheries Research* **84**(3), 314-327.

Ives, M.C., Scandol, J.P., and Greenville, J. (2013) A bio-economic management strategy evaluation for a multi-species, multi-fleet fishery facing a world of uncertainty. *Ecological Modelling* **256**, 69-84.

Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J., and Warner, R.R. (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**(5530), 629-638.

Jones, R. (1976) 'The use of marking data in fish population analysis.' (FAO Fisheries Technical Paper 153)

Kerrigan, B., Gaddes, S., and Norris, W. (2004) Review of the sustainability of fishing effort in the Queensland East Coast Trawl Fishery.

Kimura, D.K. (1980) Likelihood methods for the von Bertalanffy equation. *Fishery Bulletin* **77**(4), 765-776.

Kimura, D.K. (1981) Standardized measures of relative abundance based on modelling log (c.p.u.e.), and their application to Pacific ocean perch (Sebastes alutus). *Journal du Conseil International pour l'Exploration de la Mer* **39**, 211-218.

Kirkwood, G.P., and Somers, I.F. (1984) Growth of two species of tiger prawn, *Penaeus esculentus* and *Penaeus semisulcatus*, in the Western Gulf of Carpentaria (Australia). *Australian Journal of Marine and Freshwater Research* **35**(6), 703-712.

Leigh, G.M. (2011) Bayesian integrated likelihoods for scale parameters. (The State of Queensland)

Little, L.R., Wayte, S.E., Tuck, G.N., Smith, A.D.M., Klaer, N., Haddon, M., Punt, A.E., Thomson, R., Day, J., and Fuller, M. (2011) Development and evaluation of a cpue-based harvest control rule for the southern and eastern scalefish and shark fishery of Australia. *Ices Journal of Marine Science* **68**(8), 1699-1705.

Lloyd-Jones, L.R., Wang, Y.-G., Courtney, A.J., Prosser, A.J., and Montgomery, S.S. (2012) Latitudinal and seasonal effects on growth of the Australian eastern king prawn (*Melicertus plebejus*). *Canadian Journal of Fisheries and Aquatic Sciences* **69**(9), 1525-1538.

Lucas, C. (1974) Preliminary estimates of stocks of the king prawn, *Penaeus plebejus*, in south-east Queensland. *Australian Journal of Marine and Freshwater Research* **25**, 35-47.

Lucas, C. (1975) Does it pay to catch small prawns? *Australian Fisheries*(January), 10-11.

Lugten, G.L. (2009) *The FAO Global Record of Fishing Vessels: Issues for Pacific Island States and the Pacific Islands Forum Fisheries Agency*. In Navigating Pacific Fisheries. (Eds. Q Hanich and M Tsamenyi) pp. 104-125. (University of Woollongong: Woollongong)

MacKenzie, B.R., Alheit, J., Conley, D.J., Holm, P., and Kinze, C.C. (2002) Ecological hypotheses for a historical reconstruction of upper trophic level biomass in the Baltic Sea and Skagerrak. *Canadian Journal of Fisheries and Aquatic Sciences* **59**(1), 173-190.

Mahévas, S., Sandon, Y., and Biseau, A. (2004) Quantification of annual variations in fishing power due to vessel characteristics: an application to the bottom-trawlers of South-Brittany targeting anglerfish (Lophius budegassa and Lophius piscatorius). *Ices Journal of Marine Science* **61**(1), 71-83.

Marchal, P., Andersen, B., Caillart, B., Eigaard, O., Guyader, O., Hovgaard, H., Iriondo, A., Le Fur, F., Sacchi, J., and Santurtun, M. (2007) Impact of technological creep on fishing effort and fishing mortality, for a selection of European fleets. *Ices Journal of Marine Science* **64**(1), 192-209.

Mardia, K.V., and Jupp, P.E. (2000) 'Directional Statistics.' (John Wiley & Sons Ltd)

Masel, J.M., and Smallwood, D. (2000) Habitat usage by postlarval and juvenile prawns in Moreton Bay, Queensland, Australia. *Proc. R. Soc. Qld* **109**, 107-117.

MathWorks (2012) MATLAB The language of technical computing. R2012a edn. (The MathWorks, Inc: Natick, Massachusetts, U.S.)

MathWorks (2013) MATLAB The language of technical computing. R2013a edn. (The MathWorks, Inc: Natick, Massachusetts, U.S.)

Maunder, M.M., and Punt, A.E. (2004) Standardizing catch and effort data: a review of recent approaches. *Fisheries Research* **70**, 141-159.

McCullagh, P., and Nelder, J.A. (1989) 'Generalized Linear Models.' (Chapman & Hall)

McGarvey, R., and Feenstra, J.E. (2002) Estimating rates of fish movement from tag recoveries: conditioning by recapture. *Canadian Journal of Fisheries and Aquatic Sciences* **59**(6), 1054-1064.

Möbius, A.G. (1827) Der Barycentrische Calcul: Ein Neues Hülfsmittel zur Analytischen Behandlung der Geometrie. Leipzig: Johann Ambrosius Barth.

Montgomery, S.S. (1981) Tagging studies on juvenile eastern king prawns reveal record migration. *Australian Fisheries* **40**(9), 13-14.

Montgomery, S.S. (1990) Movements of juvenile eastern king prawns, *Penaeus plebejus*, and identification of stock along the east coast of Australia. *Fisheries Research (Amsterdam)* **9**, 189-208.

Montgomery, S.S., Courtney, A.J., Blount, C., Stewart, J., Die, D.J., Cosgrove, M., and O'Neill, M.F. (2007) Patterns in the distribution and abundance of female eastern king prawns, *Melicertus plebejus* (Hess, 1865), capable of spawning and reproductive potential in waters off eastern Australia. *Fisheries Research* **88**(1-3), 80-87. [In English]

Moxon, A.J., and Quinn, R.H. (1984) Economic survey of otter trawlers in south-east Queensland Queensland Deptartment of Primary Industries, Brisbane

Mulley, J.C., and Latter, B.D.H. (1981) Geographic differentiation of eastern Australian penaeid prawn populations. *Australian Journal of Marine and Freshwater Research* **32**, 889-895.

NSW Department of Primary Industries (2006) Determining the biological sustainability of wild fisheries in NSW: Concepts and definitions. An information paper by the Systems Research, Wild Fisheries Program., 27.

NSW Department of Primary Industries (2010) Eastern King Prawn (*Melicertus plebejus*). In Status of fisheries resources in NSW 2008/09, http://www.dpi.nsw.gov.au/research/areas/fisheries-and-ecosystems/wild-fisheries/outputs/2010/1797. (Eds. K Rowling, A Hegarty and MC Ives) pp. 392. (NSW Industry & Investment: Cronulla)

O'Callaghan, M., and Gordon, G.N.G. (2008) An individual-based stochastic hazard model of eastern king prawn (Melicertus plebejus) migration with spatially and temporally varying fishing effort. *Ecological Modelling* **218**(1-2), 73-94.

O'Neill, M.F., Campbell, A.B., Brown, I.W., and Johnstone, R. (2010) Using catch rate data for simple cost-effective quota setting in the Australian spanner crab (Ranina ranina) fishery. *ICES Journal of Marine Science* **67**(8), 1538-1552. [In English]

O'Neill, M.F., Courtney, A.J., Good, N.M., Turnbull, C.T., Yeomans, K.M., Staunton Smith, J., and Shootingstar, C. (2005) Reference point management and the role of catch-per-unit effort in prawn and scallop fisheries. Department of Primary Industries and Fisheries, No. Fisheries Research and Development Corporation (FRDC) Final Report 1999/120 Brisbane, Queensland, Australia.

O'Neill, M.F., Die, D.J., Taylor, B.R., and Faddy, M.J. (1999) Accuracy of at-sea commercial size grading of tiger prawns (*Penaeus esculentus* and *P. semisulcatus*) in the Australian northern prawn fishery. *Fishery Bulletin* **97**, 396-401.

O'Neill, M.F., and Leigh, G.M. (2006) Fishing power and catch rates in the Queensland east coast trawl fishery. Department of Primary Industries and Fisheries, Queensland. Report QI06051.

O'Neill, M.F., and Leigh, G.M. (2007) Fishing power increases continue in Queensland's east coast trawl fishery, Australia. *Fisheries Research* **85**(1-2), 84-92. [In English]

O'Neill, M.F., Leigh, G.M., Martin, J.M., Newman, S.J., Chambers, M., Dichmont, C.M., and Buckworth, R.C. (2011) Sustaining productivity of tropical red snappers using new monitoring and reference points. The State of Queensland, Department of Employment, Economic Development and Innovation. FRDC Project No. 2009/037

O'Neill, M.F., and Turnbull, C.T. (2006) Stock assessment of the Torres Strait tiger prawn fishery (*Penaeus esculentus*). Department of Primary Industries and Fisheries, No. QI05132, Queensland.

Pascoe, S., Dichmont, C.M., Brooks, K., Pears, R., and Jebreen, E. (2013) Management objectives of Queensland fisheries: Putting the horse before the cart. *Marine Policy* **37**(0), 115-122.

Pennington, M., and Vølstad, J.H. (1994) Assessing the effect of intra-haul correlation and variable density on estimates of population characteristics from marine surveys. *Biometrics* **50**(3), 725–732.

Plaganyi, E.E., Rademeyer, R.A., Butterworth, D.S., Cunningham, C.L., and Johnston, S.J. (2007) Making management procedures operational innovations implemented in South Africa. *ICES Journal Marine Science* **64**(4), 626-632.

Plummer, M., Best, N., Cowles, K., Vines, K., Sarkar, D., and Almond, R. (2006) CODA: Output analysis and diagnostics for MCMC. 0.16-1 edn. (R: A Language and Environment for Statistical Computing)

Potter, M.A. (1975) Movements of the eastern king prawn (Penaeus plebejus) in southern Queensland waters. *First Australian National Prawn Seminar*, 10-17.

Potter, M.A., and Dredge, M.C.L. (1985) Deepwater prawn resources off southern and central Queensland. In Second Australian National Prawn Seminar. (Eds. PC Rothlisberg, BJ Hill and DJ Staples) pp. 221-29. (NPS2: Cleveland, Queensland)

Punt, A.E., Buckworth, R.C., Dichmont, C.M., and Ye, Y. (2009) Performance of methods for estimating size-transition matrices using tag-recapture data. *Marine and Freshwater Research* **60**, 168–182.

Punt, A.E., Deng, R.A., Dichmont, C.M., Kompas, T., Venables, W.N., Zhou, S., Pascoe, S., Hutton, T., Kenyon, R., van der Velde, T., and Kienzle, M. (2010) Integrating size-structured assessment and bioeconomic management advice in Australia's northern prawn fishery. *ICES Journal of Marine Science* **67**(8), 1785-1801.

Punt, A.E., Hobday, D., Gerhard, J., and Troynikov, V.S. (2006) Modelling growth of rock lobsters, *Jasus edwardsii*, off Victoria, Australia using models that allow for individual variation in growth parameters. *Fisheries Research* **82**, 119-130.

QECTMP (2001) Fisheries (East Coast Trawl) Management Plan1999; Fisheries Act 1994. (Queensland Government)

Quinn, T.J., and Deriso, R.B. (1999) 'Quantitative Fish Dynamics ' (Oxford University Press)

R Development Core Team (2012) *R: A Language and Environment for Statistical Computing*. Vienna: Foundation for Statistical Computing. http://www.R-project.org.

Reid, C.R.M., and Campbell, H.F. (1999) Bioeconomic analysis of the Queensland Beam Trawl Fishery. Fisheries Research and Development Corporation (FRDC) Final Project Report #94/035. The University of Queensland, Brisbane.

Richards, L.J., Schnute, J.T., and Olsen, N. (1998) A statistical framework for the analysis of limit reference points. In Fishery Stock Assessment models. (Eds. F Funk, TJ Quinn II, J

Heifetz, JN Ianelli, JE Powers, JF Schweigert, PJ Sullivan and C-I Zhang) pp. 1037. (Alaska Sea Grant College Program Report No. AK-SG-98-01: University of Alaska Fairbanks)

Roberts, G.O., Gelman, A., and Gilks, W.R. (1997) Weak convergence and optimal scaling of random walk Metropolis algorithms. *The annals of applied probability* **7**(1), 110-120.

Robins, C.M., Wang, Y.G., and Die, D. (1998) The impact of global positioning systems and plotters on fishing power in the northern prawn fishery, Australia. *Canadian Journal of Fisheries and Aquatic Sciences* **55**(7), 1645-1651.

Ross, S.M. (1995) 'Introduction to Stochastic Dynamic Programming.' (Academic Press) 164

Rothschild, B.J. (1972) An exposition on the definition of fishing effort. *Fishery Bulletin* **70**(1), 671-679.

Ruello, N.V. (1975) Geographical distribution, growth and breeding migration of the eastern Australian king prawn *Penaeus plebejus* Hess. *Australian Journal of Marine and Freshwater Research* **26**, 343-354.

Sadovy, Y., Punt, A., Cheung, W., Vasconcellos, M., Suharti, S., and Mapstone, B. (2007) Stock assessment approach for the Napoleon fish, *Cheilinus undulatus*, in Indonesia. A tool for quota setting for data-poor fisheries under CITES Appendix II Non-Detriment Finding requirements. FAO Fisheries Circular 1023, FAO Rome.

Sainsbury, K.J. (1980) Effect of individual variability on the von Bertalanffy growth equation. *Canadian Journal of Fisheries and Aquatic Sciences* **37**, 241-247.

Schnute, J. (1985) A General Theory for Analysis of Catch and Effort Data. *Canadian Journal of Fisheries and Aquatic Sciences* **42**(3), 414-429.

Siddiqui, O., Hung, H.M.J., and O'Neill, R. (2009) MMRM vs. LOCF: A comprehensive comparison based on simulation study and 25 NDA datasets. *J. Biopharm. Stat.* **19**, 227-246.

Sklyarenko, E.G. (2011) Barycentric coordinates. In Encyclopedia of Mathematics. (http://www.encyclopediaofmath.org/index.php?title=Barycentric_coordinates&oldid=15139 http://books.google.com.au/books?id=eFPluv_UqFEC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false)

Sparre, P., and Venema, S.C. (1998) Introduction to tropical fish stock assessment. Part 1. Manual. FAO Fisheries Technical Paper No, 306.1, Rev.2. Food and Agriculture Organisation, Rome, Italy.

Sumaila, U.R., and Hannesson, R. (2010) Maximum economic yield in crisis? *Fish and Fisheries* **11**(4), 461-465. [In English]

Taylor-Moore, N., Bibby, J., Burger, E., Dexter, J., Henderson, T., Norris, W., and Switala, J. The Business of Fishing: Queensland, Australia 1997-98. In 'Proceedings of International Institute of Fisheries Economics and Trade (IIFET) 10th IIFET Conference, July 10-14, 2000', 2000, Corvallis, Oregon, U.S.A. , pp. 1-10

Troynikov, V.S. (1998) Probability density functions useful for parametrization of heterogeneity in growth and allometry function. *Bulletin of Mathematical Biology* **60**, 1099-1122.

Troynikov, V.S., and Walker, T.I. (1999) Vertebral size-at-age heterogeneity in gummy shark harvested off southern Australia. *Journal of Fish Biology* **54**, 863-877.

Turnbull, C.T., Tanimoto, M., O'Neill, M.F., Campbell, A., and Fairweather, C.L. (2009) Torres Strait Spatial Management Research Project 2007-09.

Walters, C. (2003) Folly and fantasy in the analysis of spatial catch rate data. *Canadian Journal of Fisheries and Aquatic Sciences* **60**(12), 1433-1436.

Walters, C.J., and Martell, S.J.D. (2004) 'Fisheries ecology and management.' (Princeton University Press: Princeton and Oxford)

Wang, Y.-G., Thomas, M.R., and Somers, I.F. (1995) A maximum likelihood approach for estimating growth from tag-recapture data. *Canadian Journal of Fisheries and Aquatic Sciences* **52**(2), 252-259.

Wang, Y.G., and Die, D. (1996) Stock-recruitment relationships of the tiger prawns (Penaeus esculentus and Penaeus semisulcatus) in the Australian Northern Prawn Fishery. *Marine and Freshwater Research* **47**(1), 87-95.

Wang, Y.G., and Thomas, M.R. (1995) Accounting for individual variability in the von Bertalanffy growth model. *Canadian Journal of Fisheries and Aquatic Sciences* **52**(7), 1368-1375.

Wang, Y.G., and Wang, N. (2012) A Retrospective Evaluation of Sustainable Yields for Australia's Northern Prawn Fishery. *Fisheries* **37**(9), 410-416. [In English]

Wright, P.J., Galley, E., Gibb, I.M., and Neat, F.C. (2006) Fidelity of adult cod to spawning grounds in Scottish waters. *Fisheries Research* **77**(2), 148-158.

Ye, Y. (2000) Is recruitment related to spawning stock in penaeid shrimp fisheries? *Ices Journal of Marine Science* **57**(4), 1103-1109. [In English]

Young, P.C. (1978) Moreton Bay, Queensland: a nursery area for juvenile penaeid prawns. *Australian Journal of Marine and Freshwater Research* **29**, 55-75.

Young, P.C., and Carpenter, S.M. (1977) Recruitment of postlarval penaeid prawns to nursery areas in Moreton Bay, Queensland. *Australian Journal of Marine and Freshwater Research* **28**, 745-773

13 Appendix 1. Intellectual property

The following manuscripts in the Appendices should be cited as papers rather than as part of the report. A full list of publications from the project is provided in 10 Planned outcomes.

Appendix 7. Fishing power and standardised catch rates: Implications of missing vessel-characteristic data from the Australian eastern king prawn fishery

Appendix 8. Quantifying northward movement rates of eastern king prawns along eastern Australia

Appendix 9. Stochastic growth of the eastern king prawn (*Melicertus plebejus*) harvested off eastern Australia,

Appendix 10. Linking spatial stock dynamics and economics: Evaluation of indicators and fishery management for the travelling eastern king prawn (*Melicertus plebejus*)

Appendix 11. Latitudinal and seasonal effects on growth of the Australian eastern king prawn (Melicertus *plebejus)*

14 Appendix 2: Staff

(in alphabetical order)

- Dr. Matias Braccini, Fishery Resource Assessment Scientist (DAFF)
- Dr Tony Courtney, Principal Fisheries Biologist (DAFF)
- Mr. Marco Kienzle, Fishery Resource Assessment Scientist (DAFF)
- Ms. Michelle Landers, Fisheries technician (DAFF)
- Dr. George Leigh, Fishery Resource Assessment Scientist (DAFF)
- Mr Michael O'Neill, Fishery Resource Assessment Scientist (DAFF)
- Dr. Sean Pascoe, Fisheries Economist (CSIRO)
- Mr. Andrew Prosser, Fisheries Biologist (DAFF)

15 Appendix 3. Recruitment dynamics of eastern king prawns in their northern distribution (Objective 1)

This section of the report addresses Objective 1. *Investigate the recruitment dynamics of eastern king prawns in their northern-most distribution (i.e., North Reef – Swain Reefs area).*

15.1 ABSTRACT

Tagged prawn recaptures, sample length-frequencies, commercial catch grading data and logbook data were used to infer temporal and spatial patterns in recruitment of EKP in the northern part of the fishery (22°–24°S). Tag-recaptures showed the prawns migrate in an east-north-easterly direction from the vicinity of North Reef to deeper offshore waters. A dearth of a) reported logbook catches west of the Capricorn-Bunker Islands and b) Fraser Island tagged prawns that were caught north of the island, suggest that the majority of EKP caught in the northern part of the fishery recruit from offshore reefs, including North Reef, associated with the Capricorn–Bunker group, which is about 100 km from the coast. Recruitment of prawns from adjacent shallow inshore coastal habitats, which is typical for most penaeid prawns, does not appear to occur in this region. Both the seasonality and spatial patterns in recruitment were reflected in the composition of commercial catch grades. Catch rates of the smallest commercial grade (21-30 prawns per pound) peaked in December and January, while catches of a slightly larger grade (i.e., 21-30 prawns per pound) peaked in March. These temporal and spatial patterns can be used by managers, stakeholders and scientists to reduce the risk of overfishing and improve modelling of the fishery.

15.2 INTRODUCTION

Eastern king prawns (EKP) are a commercially important species in the Queensland east coast trawl fishery. Logbook data indicate that about 1900 t of EKP, valued at about $30 million, are landed annually in Queensland, with an additional 500-700 t caught in New South Wales. The fishery extends over much of Australia's eastern continental shelf (21-38°S).

Understanding the temporal and spatial patterns in recruitment in prawn fisheries is important for modelling the stock, evaluating harvest strategies and preventing overfishing. Post-larval and juvenile *M. plebejus* typically utilise shallow (i.e., < 10 m) inshore coastal habitats, including bare sand and seagrasses, before migrating to deeper areas where they are trawled (Masel and Smallwood 2000; Young and Carpenter 1977). Courtney *et al.* (1995) described the seasonal and spatial patterns in recruitment of *M. plebejus* and other prawn species in Moreton Bay, based on monthly sample length-frequency analysis of the population over a two-year period. Large numbers of small (i.e., 15-25 mm carapace length CL) *M. plebejus* recruit rapidly to the Moreton Bay trawl fishing grounds in October–November before migrating to deeper waters outside the Bay where they are also caught by an offshore fleet. In Queensland adults are typically trawled in depths between 90 m and 260 m.

Previous tag-recapture studies have shown that EKP commonly undertake a significant northerly migration as they grow, often exceeding hundreds of kilometres (Braccini *et al.* 2012b; Glaister *et al.* 1987; Lucas 1974; Montgomery 1990; Ruello 1975). These studies not only provide information on growth and mortality rates, but also information on recruitment dynamics (i.e., where young prawns come from, how fast they migrate and direction of movements).

Although a significant proportion of the EKP catch is taken in the northern part of the fishery between 22°S and 24°S, little is known about the prawn recruitment dynamics in this part of the fishery. As the fishery extends northwards, it also occurs further from the coast and in progressively greater depths. The Swain Reefs (22°S), which approximate the northern-most distribution of the fishery, are about 250 km from the coast and it is unknown where the prawns that are caught in this area come from. Most tagging studies have been conducted much further south in New South Wales and have provided little information on the northern part of the fishery. Ruello (1975) reported that the fishery only extended northward to Fraser Island (25°S) in the 1970s, and it was not until Potter and Dredge (1985) undertook a deepwater exploratory survey in 1983-84 that the fishery expanded offshore in central Queensland (i.e., 22-24°S).

Some Queensland trawl fishers have expressed concern that the prawns are growth overfished in this northern part of the fishery and have suggested a spatial closure to address the problem (this is addressed in 18 Appendix 6. Yield and value per recruit assessment of the proposed North Reef closure on eastern king prawns). However, without information on the timing of recruitment, the spatial source of prawns or the direction of movement in the area, it is difficult to evaluate such management measures. This section of the report investigates the recruitment dynamics of EKP in their northern distribution to support the fishery's management decision making process.

15.3 MATERIALS AND METHODS

The recruitment dynamics of EKP between the Swain Reefs (22°S) and Fraser Island (25°S), were investigated using tag-recapture experiments, and by analysing fishery-independent length-frequency data, commercial catch grading data and logbook data.

15.3.1 Tag-recapture experiments

To better understand recruitment, and in particular, the likely location of nursery grounds and the direction of movement of sub-adult and adult prawns in the northern part of the fishery, two tag-release experiments were carried out in the region – one in January 2009 which chartered the *FV Somatina* and one in February 2010 which chartered the government *RV Gwendoline May*. We used individually numbered size 4s polyethylene streamer tags (PST) with standard 58 mm applicator needles, manufactured by Hallprint (South Australia).

A single tag was inserted through the first abdominal segment of each prawn using the application needle, between the ventral nerve chord and the dorsally-located gut and gonads (Figure 15-1). The needle was then torn off the tag and discarded, leaving the tag in the prawn. To reduce stress and maximise survival of the prawns, the distance of each trawl used to initially capture the prawns was set at 0.5 nautical miles (nm), which limited the trawl duration to about 15 minutes. The release location, size (mm, CL) and sex of each tagged prawn were recorded. On the back deck, tagged prawns were placed inside a purposely-designed release cage (Figure 15-1) that was submerged in seawater in a large tank. When between 100 and 150 prawns were in the cage, the vessel was brought to a halt, the lid of the cage slid closed and the cage lowered to the sea bottom. The lid was then pulled open from the surface, allowing the prawns to disperse near the bottom, before the cage was hauled back the vessel.

Figure 15-1. Left – lowering the release cage with tagged prawns inside. When the cage contacts the bottom, the sliding lid is pulled open from the vessel with a rope. Right – tagged eastern king prawn prior to release. Photos taken on board the *FV Somatina* which was chartered for the first tagging experiment in January 2009.

Fishers and processors were provided with tagged-prawn recapture kits shortly before the prawns were released. Kits included phone numbers for project staff, plastic bags to retain recaptured tagged prawns, waterproof labels to record the tag number, location, recapture date, vessel name and fisher contact details. The kits were then collected periodically by staff over the following two years. A small reward (i.e., $10 scratch-it lottery ticket) was provided to fishers for each recaptured prawn, in addition to information on the prawn's speed and direction of movement, time-at-liberty, sex and growth. As further incentive, all fishers who participated in the program went into the draw for a $3000 travel voucher, which was drawn at the end of the project (won by Mr. Shane Paulsen, Bundaberg 25th May 2012).

15.3.2 Length-frequency analysis

A total of 83 sites were sampled during the two charters – 54 sites in 2009 and 29 in 2010 (Figure 15-2). Each site consisted of one 0.5 nm transect. Although not all EKP caught at each site were tagged and released, all individuals were sexed and measured (CL, mm), providing a spatial distribution of length-frequency data. By examining the length-frequency distributions in relation to their location, an understanding of the likely nursery grounds and prawn movements in the region can be derived.

Multidimensional scaling (MDS) and cluster analysis were used to examine how similar length frequency distributions were and hence, how sites might be grouped. Male and female distributions were analysed separately due to the differences in the sizes attained by the sexes, and sites where fewer than 10 individuals were caught were omitted. The statistical software package PRIMER (Clarke and Warwick 1994) was used to undertake the analyses, which were based on counts at length-site matrices. Prior to undertaking the analyses, the number of prawns caught at each site was standardised, to total 100 and the data square-root transformed. Euclidean distance for each pair of samples (i.e., site 1 compared with site 2, site 1 with site 3, site 1 with site 4, etc.) was estimated and used in the MDS. Hierarchical cluster analysis was then used to examine groupings at two distance measures of 8 and 10.

15.3.3 Analysis of catch grading data

Three Queensland fishing companies voluntarily provided grading data on the composition of their daily EKP catches. Data provided by Murphy's Australian Ocean King Prawn Company were particularly detailed and consisted of over 11,000 daily records of graded catch from five vessels over a more than a decade (i.e., 1997–2009). The data show each vessel's daily catch processed to 5 kg boxes with each box allocated to one of six size classes or grades (Table 15-1), with ‘soft and broken prawns’ processed as an additional category. The grading data were mainly obtained between 22ºS and 24ºS from logbook grids V26, W26 and W27 (Swain Reefs), V28 and U28 (Archer Shoal), U29 (east of North Reef) and U30 and V30 (Lady Musgrave Island) (Figure 15-2).

Table 15-1. Prawn catch grades commonly used in the EKP fishery. Size range (in mm CL) of males and females corresponding to each grade are provided. Note that males don’t grow large enough to contribute to the large grades. As such, the large size grades are comprised entirely of females.

Prawn Grade	**Weight range (g)**	**Min CL (mm) Male**	**Min CL (mm) Female**
Under 6 (6 prawns or fewer per pound)	>76	-	52
6-8 (6-8 prawns per pound)	56-75	-	47
8-10 (8-10 prawns per pound)	45-55	43	43
10-15 (10-15 prawns per pound)	30-44	37	37
16-20 (16-20 prawns per pound)	23-29	33	33
21-30 (21-30 prawns per pound)	<23	29	28

Variation in the number of boxes in each grade, combined with information on the date of capture and the vessel’s location recorded in the logbook database, can be used to better understand the prawn’s population dynamics, including the timing and location of recruitment, as well as movement patterns. For example, the number of boxes of prawns in small grades (i.e., 16-20 and 21-30) caught per boat-night provides information on where and when recruits enter the fishery. Generalized linear modelling (GLM) was used to examine the variation in the number of boxes of each size grade. An example of the data format, including the response variable (i.e., number of 5 kg boxes) and factors examined in the modelling (i.e., grade, year, month, logbook grid, lunar phase and vessel) is provided in Table 15-2.

Table 15-2. Example of the grading data analysed using GLM.

Date	**Day**	**Month**	**Year**	**Vessel identifier**	**Grade**	**Number of 5 kg boxes**	**Logbook Grid**	**Lunar phase**
12-Sep-97	12	9	1997	FBAX	U10-15	7	W27	Waxing
12-Sep-97	12	9	1997	FBAX	U16-20	7	W27	Waxing
12-Sep-97	12	9	1997	FBAX	S and B	4	W27	Waxing
13-Sep-97	13	9	1997	FBAX	U6	3	W27	Full moon
13-Sep-97	13	9	1997	FBAX	U8-10	4	W27	Full moon
13-Sep-97	13	9	1997	FBAX	U10-15	7	W27	Full moon
13-Sep-97	13	9	1997	FBAX	U10-15	6	W27	Full moon
13-Sep-97	13	9	1997	FBAX	U16-20	6	W27	Full moon
13-Sep-97	13	9	1997	FBAX	S and B	3	W27	Full moon
14-Sep-97	14	9	1997	FBAX	U6	3	W27	Full moon
14-Sep-97	14	9	1997	FBAX	U8-10	4	W27	Full moon
14-Sep-97	14	9	1997	FBAX	U10-15	7	W27	Full moon
14-Sep-97	14	9	1997	FBAX	U10-15	5	W27	Full moon

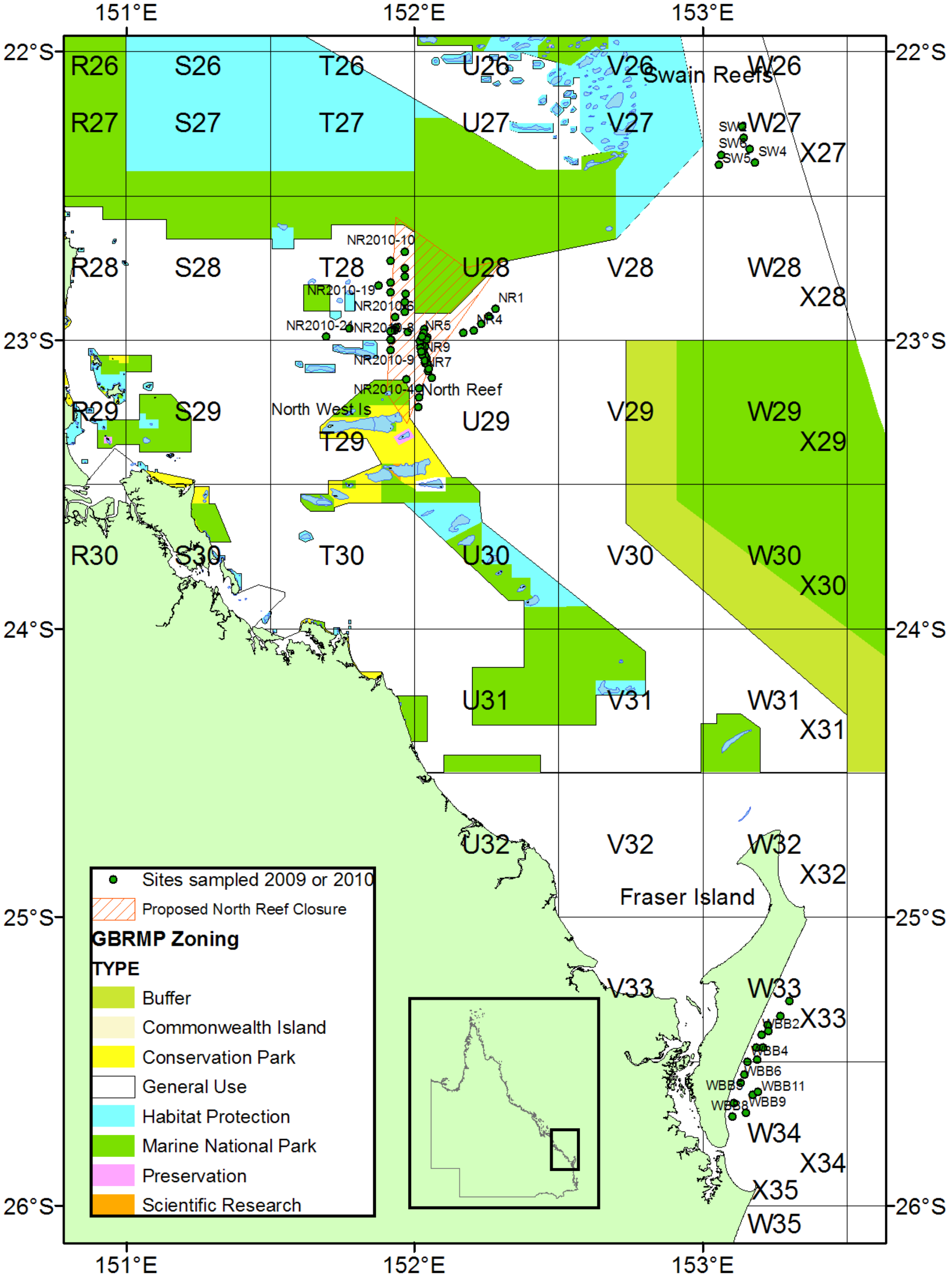


Figure 15-2. The northern section of the eastern king prawn fishery on the Queensland east coast (i.e., 22—24ºS). A total of 83 0.5 nm sites (green dots) were sampled in 2009 and 2010 to obtain prawns for tagging and length-frequency data. Sampling concentrated on three areas, Fraser Island (Wide Bay or WB sites), North Reef (NR sites) and the Swain Reefs (SW sites). Logbook grids and the proposed closed area are also shown.

15.3.4 Logbook catch and effort data

Prawn trawl fisheries often display seasonal peaks in monthly catches, effort and catch rates during or shortly after recruitment. The size of the exploited population peaks at this time and declines over the following months. An analysis of EKP logbook data from 1988 to 2010 was therefore carried out to determine whether temporal or spatial trends in recruitment could be discerned in the region.

15.4 RESULTS

15.4.1 Prawn movements

A total of 3766 eastern king prawns were tagged and released during the two charters (Table 15-3). Most of the tagging occurred in 2009, while the 2010 charter undertook more exploratory trawls in shallow, mainly-untrawled areas near North Reef, in search of small (i.e., in the size range 20–35 mm) prawns that were considered indicative of recruitment.

Length-frequency distributions of the tagged prawns at the time of release show that prawns from Fraser Island were smaller than those from the North Reef area (Figure 15-3). As prawn size generally increases with depth, this seems to be partly explained by the depths the prawns were caught in. The average depth of the Fraser Island and North Reef trawls was 27.0 m and 90.8 m, respectively. The average depth for the Swain Reef trawls was 151.9 m, but as the prawns from this area were all large and moribund when brought to the surface (possibly due to being trawled from greater depths), none were tagged.

Table 15-3. Summary of tagged eastern king prawn releases.

General area	**Release date**	**Female**	**Male**	**Sex unknown**	**Grand Total**
Fraser Island 2009	25/01/2009	201	180		381
	26/01/2009	362	371	7	740
	27/01/2009	147	278		425
Fraser Island 2009 Total		710	829	7	1546
North Reef 2009	22/01/2009	148	295		443
	23/01/2009	406	335	1	742
	24/01/2009	150	138	1	289
North Reef 2009 Total		704	768	2	1474
North Reef 2010	13/02/2010	56	34		90
	14/02/2010	66	71		137
	15/02/2010	200	181		381
	16/02/2010	69	69		138
North Reef 2010 Total		391	355		746
Grand Total		**1805**	**1952**	**9**	**3766**

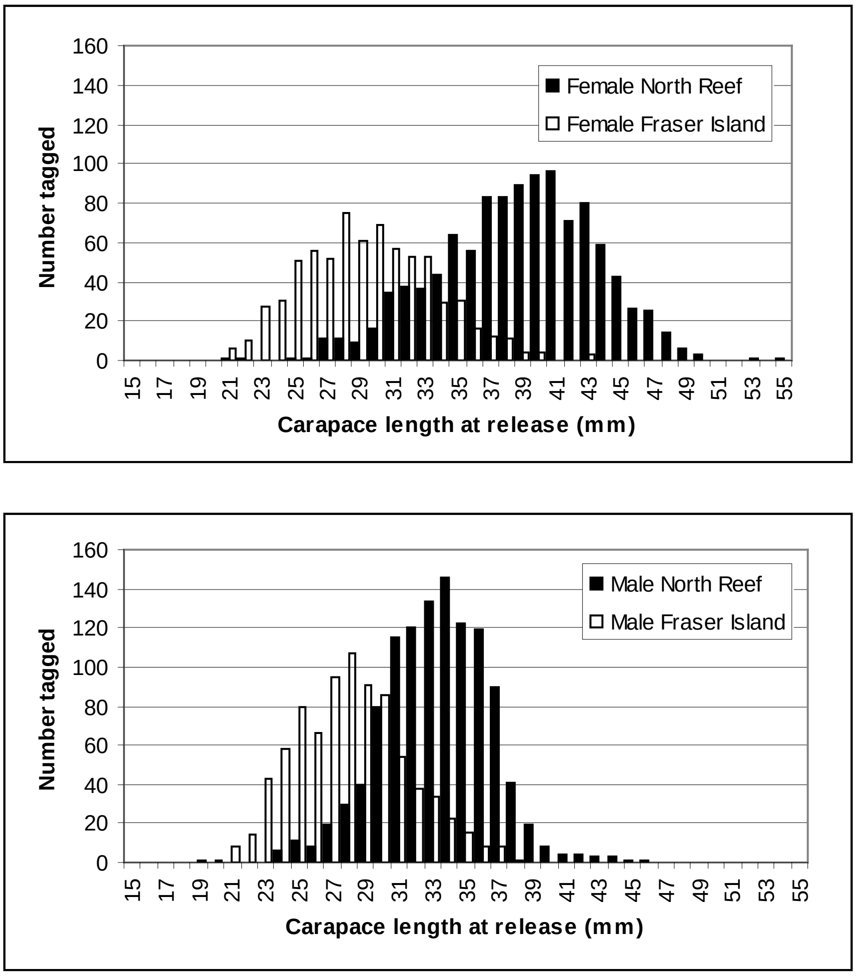


Figure 15-3. Length-frequency distributions of tagged male and female EKP from the vicinity of North Reef and Fraser Island.

Obvious size differences between the sexes were apparent at both areas, with males numerically dominating small size classes (20-40 mm CL) and females dominating the larger (30-50 mm CL). Slightly more males (n=1952) were tagged and released than females (n=1805), probably because the taggers sought smaller sizes (~20-30 mm CL), as they have potential to result in longer periods at liberty, and hence provide more information on movements and growth than larger/older age classes.

Of the 3766 tagged prawn releases, fishers and processors provided data for a total of 84 individuals – a recapture rate of 2.2%, which is low compared to previous EKP tagging studies. Five of the 84 recaptures had no spatial or temporal coordinates provided when they were returned to project staff, preventing them from being included in movement analyses. An additional prawn was provided without a cephalothorax which excluded it from growth analyses. Recapture rates of prawns tagged and released at Fraser Island were very low and about half that of North Reef (Table 15-4).

Table 15-4. Summary of recapture details for prawns tagged and released near Fraser Island and North Reef in 2009 and 2010. Standard errors in brackets.

	Number tagged	Number and percentage recaptured	Average distance moved (nm)	Average number days at liberty	Average speed (nm/day)
North Reef (23ºS)					
Females	1095	39 (3.56%)	38.13 (3.68)	172.5 (11.8)	0.25 (0.02)
Males	1123	27 (2.40%)	33.80 (4.11)	231.3 (29.1)	0.18 (0.02)
Fraser Island (25º30'S)					
Females	710	9 (1.27%)	18.12 (5.25)	72.0 (15.5)	0.23 (0.06)
Males	829	6 (0.72%)	21.49 (6.87)	104.5 (34.8)	0.26 (0.10)

The longest period at liberty was 542 days by a male that was released on 22/1/2009 and recaptured on 18/7/2010. Two individuals, one male and one female that were provided with only approximate recapture dates, were estimated to be at liberty for about 540 days. Another male that was tagged on 24/1/2009 was recaptured 532 days later on 10/7/2010. Another male was also at liberty for 503 days. About half of all recaptures were prawns that were at liberty for between 101 and 200 days (Table 15-5).

Table 15-5. The number of tagged prawns that were recaptured against varying periods at liberty. Data from both charters and sexes are pooled.

Period at liberty (days)	Number caught
1-101	20
101-200	42
201-300	6
301-400	6
401-500	2
501-600	5

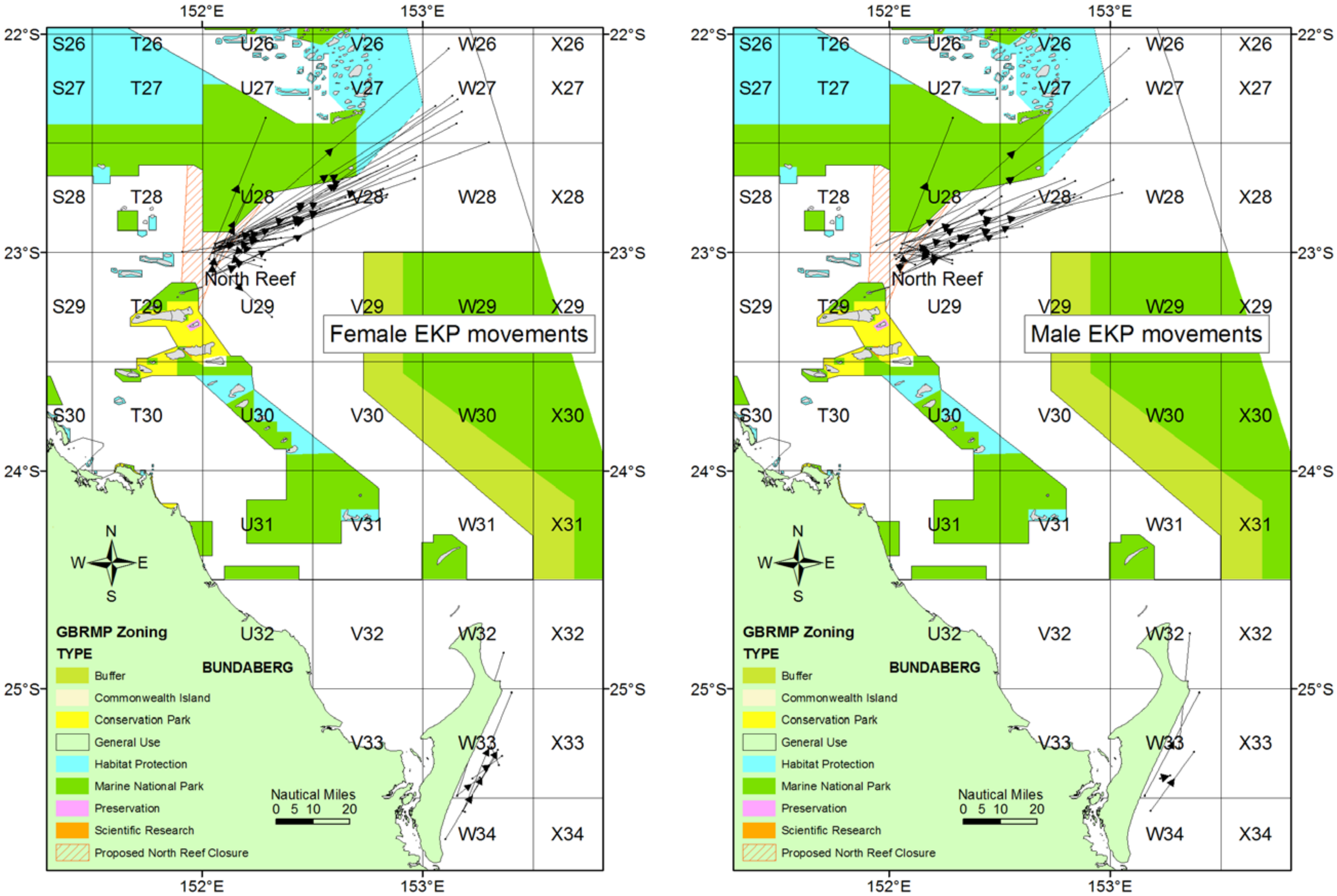


Figure 15-4. Distance moved and direction of movement for tagged eastern king prawns released in January 2009 and February 2010. Arrows indicate direction of movement.

Fraser Island prawns generally moved north-northeast, while the North Reef prawns generally moved east-northeast (Figure 15-4). A generalised linear model (GLM) with a normal distribution and identity link function used to examine the effect of area (i.e., Fraser Island and North Reef) and sex (i.e., male and female) found that the distance moved by recaptured prawns differed significantly between areas (Variance ratio=6.56, d.f.=1, P=0.012). While North Reef females generally moved greater distances than males (Table 15-4), there was no significant sex effect, nor was the area.sex interaction term significant. Adjusted mean movements for sexes combined were 19.43 s.e. 6.195 nm and 36.44 s.e. 2.644 nm for Fraser Island and North Reef, respectively.

The average number of days at liberty for North Reef prawns was more than twice that of the Fraser Island prawns (Table 15-4). A GLM with a Poisson error distribution and logarithm link function confirmed that both area (Deviance ratio, DR =958.25, d.f.=1, P<0.001) and sex (DR=303.11, d.f.=1, P<0.001) significantly affected the period at liberty. The interaction term was not significant. Females were at liberty for significantly shorter periods than males.

The speed of movement of recaptured prawns varied between a mean of 0.18 nm per day for males released near North Reef and 0.26 nm per day for males released at Fraser Island (Table 15-4). Two types of GLM were used to examine area and sex effects on speed; the first used a normal distribution with identity link function, and the second a gamma distribution with logarithm link. For both approaches, neither area nor sex, nor their interaction term significantly affected the speed at which the prawns moved.

15.4.2 Length-frequency analysis

A total of 12,485 *M. plebejus* were sampled from the 83 sites from the two charters in 2009 and 2010. Males (6608) were more numerous than females (5877), especially in the 20-40 mm CL size range (Figure 15-5). Females dominated the 40-60 mm CL size classes. The maximum sizes sampled for males and females were generally consistent with the maximum attainable size (L_∞) for each sex (Glaister *et al.* 1987; Lloyd-Jones *et al.* 2012). While some overlap in distributions was apparent, each of the three areas (i.e., Fraser Island, North Reef and Swain Reefs) was associated with a specific size-frequency. Fraser Island had the smallest prawns, while North Reef displayed an intermediate size distribution, while the Swain Reefs was characterised by large individuals.

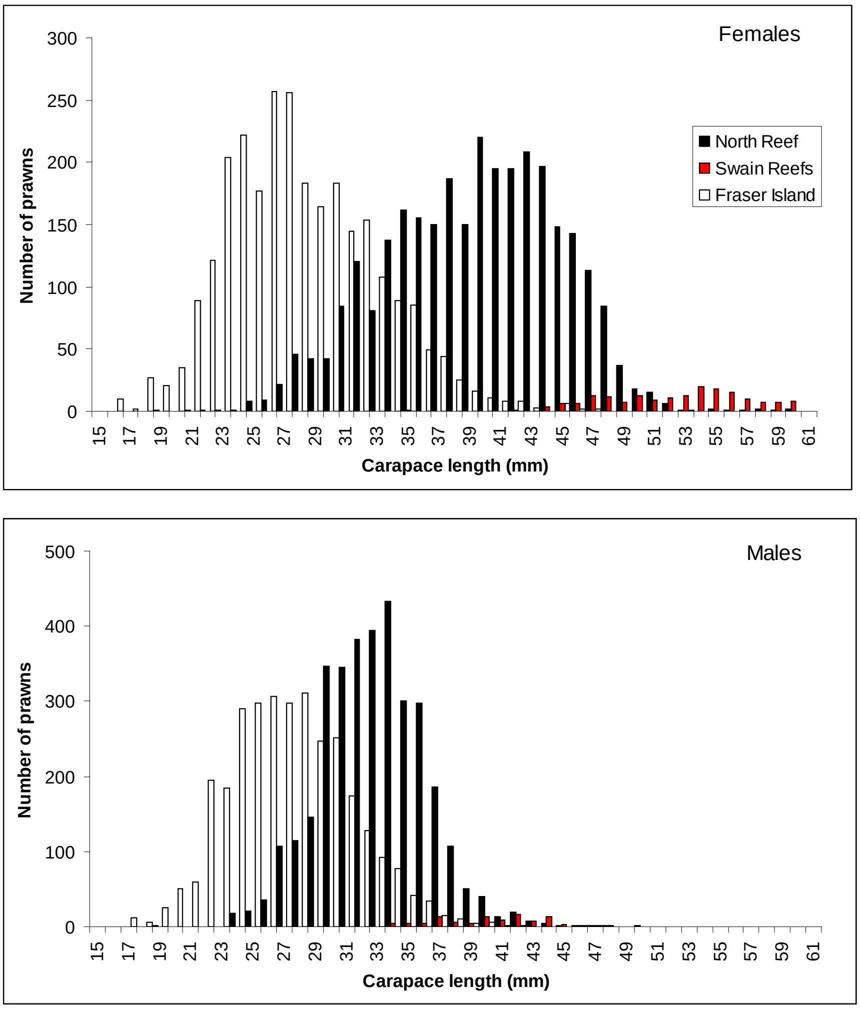


Figure 15-5. Length-frequency distributions of male and female *M. plebejus* from the 83 sites sampled in the northern part of the fishery in 2009 and 2010.

MDS confirmed that sites could be clustered into three groups at an arbitrary distance of 10 (Figure 15-6). Fraser Island sites (i.e., WB sites in Figure 15-2), which produced the smallest prawns sampled, mainly clustered into one group on the left side of Figure 15-6. North Reef sites (i.e., NR sites), which produced intermediate size classes, mainly clustered into a central group, while the Swain Reef sites (SW sites) formed a distinct group on the right. The trends were very similar for both sexes.

15.4.3 Commercial catch grading data

A summary of Murphy's grading data used in the analyses is provided in Table 15-6. The dataset is comprised of 394,950 five-kilogram boxes from five vessels between September 1997 and April 2009. Eighty-four percent of boxes were reported from five logbook grids (W27 east of Swain Reefs, V28 Archer Shoal, U28 North Reef, W28 east Archer Shoal, and U29 Capricorn-Bunker Islands).

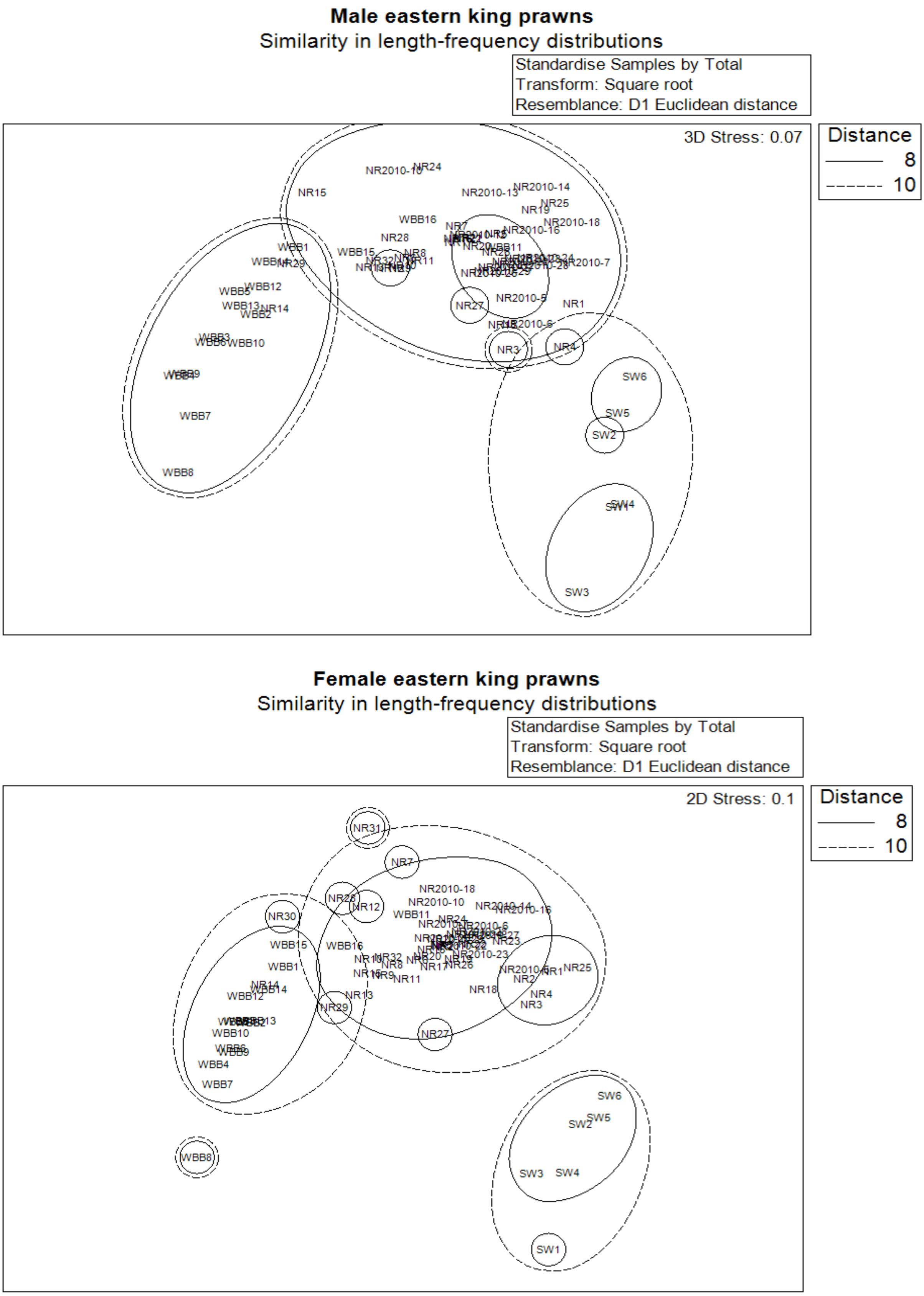


Figure 15-6. Multidimensional scaling and cluster analysis of eastern king prawn length-frequencies from 83 sites (some sites omitted due to small sample size) in the northern part of the fishery. At a distance of 10, three broad groupings are apparent.

Table 15-6. Summary of grading data. Numbers of 5 kg boxes in each size grade from each logbook grid, provided by five vessels over a period of approximately 10 years.

Grid	S and B	U10-15	U16-20	U21-30	U6	U6-8	U8-10	Total	Percentage
No grid	2428	5274	3037	70	1937	5058	4163	21967	5.56
T27	7	9	8	0	6	13	17	60	0.02
T28	15	15	20	0	6	14	19	89	0.02
T29	4	5	6	0	0	1	1	17	0.00
U26	4	20	7	0	6	0	11	48	0.01
U27	326	953	285	12	665	995	446	3682	0.93
U28	7164	13707	7889	201	4534	14353	11324	59172	14.98
U29	2189	5729	3390	205	1477	3762	3912	20664	5.23
U30	329	1337	491	16	309	840	620	3942	1.00
U33	4	8	2	0	3	6	2	25	0.01
V24	4	15	10	0	16	3	8	56	0.01
V25	13	40	35	0	45	0	50	183	0.05
V26	308	1160	494	22	905	377	560	3826	0.97
V27	423	959	303	0	882	1796	722	5085	1.29
V28	10006	21746	9935	112	12054	32605	16879	103337	26.16
V29	488	581	499	6	270	519	599	2962	0.75
V30	632	2398	1168	99	442	1214	1144	7097	1.80
V31	81	305	186	12	35	131	128	878	0.22
V32	49	80	60	0	7	111	146	453	0.11
W23	2	18	0	0	28	35	17	100	0.03
W24	2	6	0	0	3	2	2	15	0.00
W25	4	3	0	0	11	11	2	31	0.01
W26	330	1147	426	1	939	680	862	4385	1.11
W27	9068	23358	5964	46	25449	31370	16172	111427	28.21
W28	3220	8801	1052	12	9554	10202	5823	38664	9.79
W29	114	233	83	2	273	129	192	1026	0.26
W30	8	45	0	0	25	39	25	142	0.04
W31	18	94	27	0	45	56	43	283	0.07
W32	2	10	1	0	1	4	4	22	0.01
W39	8	17	0	0	36	21	1	83	0.02
X26	3	6	8	0	5	0	21	43	0.01
X27	10	38	3	0	42	48	21	162	0.04
X28	54	127	53	0	55	161	61	511	0.13
X30	6	14	18	0	2	11	11	62	0.02
X32	2	14	4	0	2	6	6	34	0.01
X34	1	6	0	0	2	3	5	17	0.00
X35	5	79	11	0	8	29	46	178	0.05
X36	170	962	258	1	46	274	582	2293	0.58
X37	65	503	162	3	31	106	277	1147	0.29
X38	81	363	177	12	4	42	103	782	0.20
Totals								**394950**	**100**

When the number of boxes is summed for January (i.e., vessels and years pooled), the composition of the catch is dominated by smaller grades (i.e., 16-20 and 10-15 prawns per pound) in logbook grids near North Reef (i.e., U28 and U29) (Figure 15-7). In contrast, when boxes are summed for July (vessels and years pooled), the catch composition is mainly comprised of large grades (i.e., fewer than 6 prawns per pound and 6-8 prawns per pound) in deeper offshore grids W27 and W28. These trends demonstrate how such grading data may be used to detect recruitment and describe movement patterns in the region.

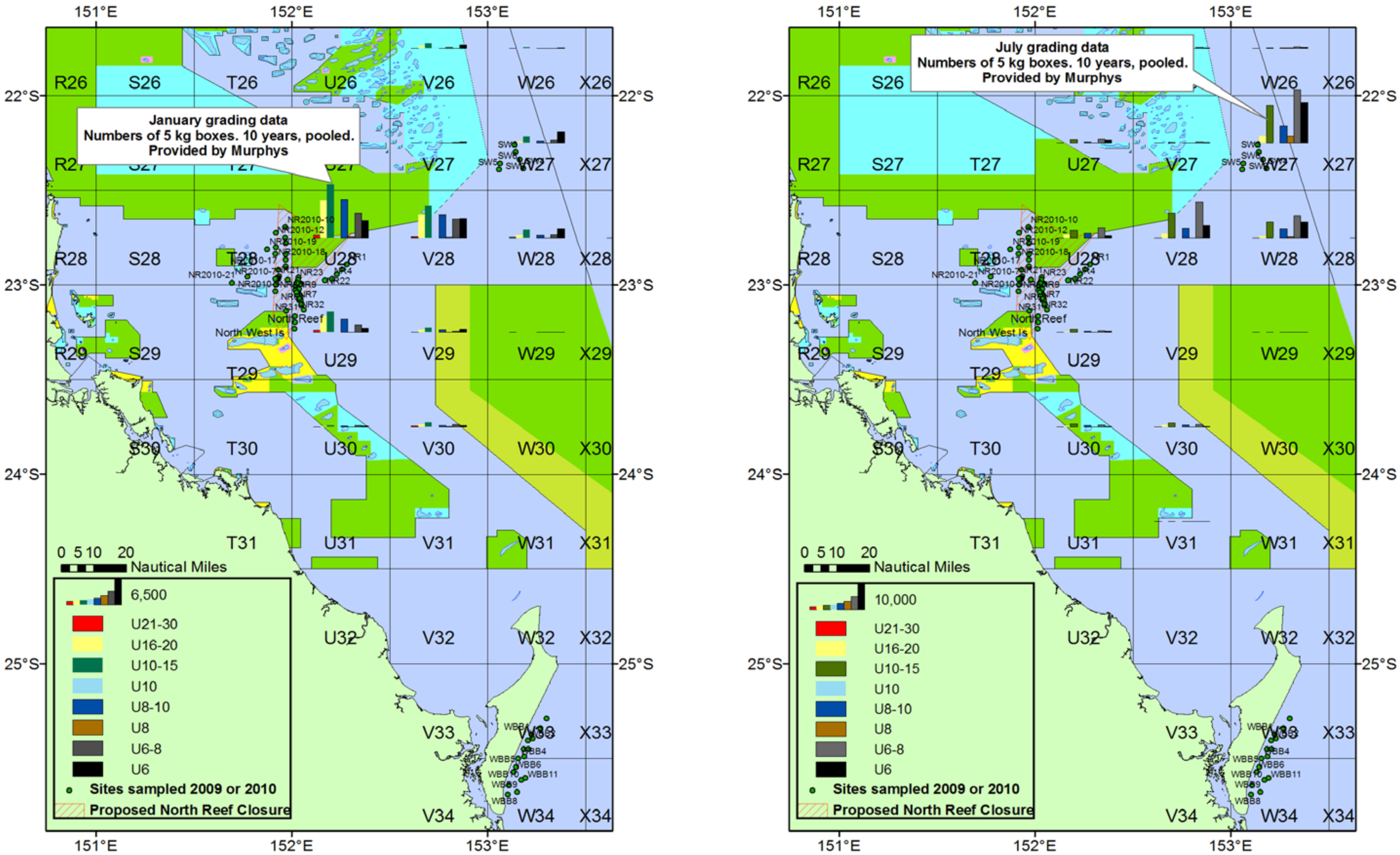


Figure 15-7. Breakdown of eastern king catch composition in the northern part of the fishery by logbook grid for January and July. Data were pooled across vessels and years. Green, blue yellow shaded areas represent different zones in the Great Barrier Reef Marine Park.

To avoid aliasing due to a relatively large number of logbook grids that only included a small percentage of the data, modelling was undertaken using data from the five grids (listed above) that accounted for 84% of all boxes. Two GLM types were explored – a Poisson distribution with logarithm link function and a negative binomial distribution with logratio link. As the Poisson model resulted in residuals that more closely resembled a normal distribution (Table 15-7) compared to the negative binomial model, it was preferred for examining variation in the grading data. The three-way interaction (Grade.Month.Grid) explained relatively little variation (DR = 9.93, Table 15-7) and was therefore deemed as unnecessary. The model was therefore re-run limiting interactions to two-way terms (i.e.,Grade.Month and Grade.Grid).

Table 15-7. Accumulated analysis of deviance for the Poisson model of grading data. The response variable is the number of 5 kg boxes in each prawn size grade per boat-night.

Change	**d.f.**	**Deviance**	**mean deviance**	**deviance Ratio**	**approx F pr.**
+ Grade	6	151973.585	25328.931	11341.96	<.001
+ Month	11	20980.471	1907.316	854.07	<.001
+ Grid	4	119.490	29.872	13.38	<.001
+ Grade.Month	66	34544.928	523.408	234.38	<.001
+ Grade.Grid	24	12259.346	510.806	228.73	<.001
+ Month.Grid	44	2583.197	58.709	26.29	<.001
+ Grade.Month.Grid	264	5853.029	22.171	9.93	<.001
+ Year	11	8426.865	766.079	343.04	<.001
+ Phase	3	1091.174	363.725	162.87	<.001
+ Vessel	4	153.641	38.410	17.20	<.001
Residual	68892	153850.065	2.233		
Total	69329	391835.791	5.652		

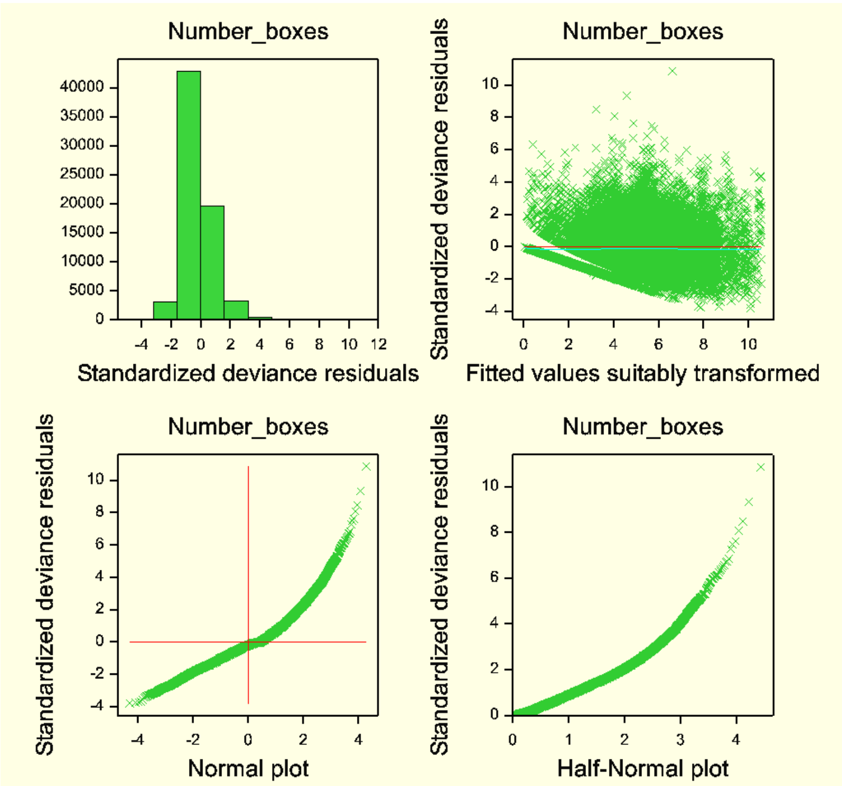


Figure 15-8. Composite residual plots from the Poisson model of the grading data in Table 15-7.

The adjusted catch rates of the smallest prawn grade (i.e., 21-30 prawns per pound) derived from the model peaked in January and December (Figure 15-9), suggesting that small prawns (i.e., prawns weighing 15-22 g) recruit to the fishery in the region at this time. The results are consistent with the recruitment pattern of EKP in the inshore waters of Moreton Bay, where very small prawns (i.e., 5-10 g) recruit to the Bay fishery in October-November before emigrating offshore 1-2 months later (Courtney *et al*. 1995; Lucas 1974). Catch rates of the slightly larger sizes (i.e., 16-20 per pound) increased from January and peaked in March, while catch rates of prawns in the size range 10-15 per pound were relatively consistent throughout the year.

Catch rates in the 8-10 prawns per pound grade peaked in March, while catch rates in the 6-8 prawns per pound grade, which were the most numerous grade, peaked from May to June. Catch rates of prawns in the largest size grade (i.e., fewer than 6 prawns per pound) were relatively consistent all year round, varying between about 4 and 7 boxes per boat-night (Figure 15-9).

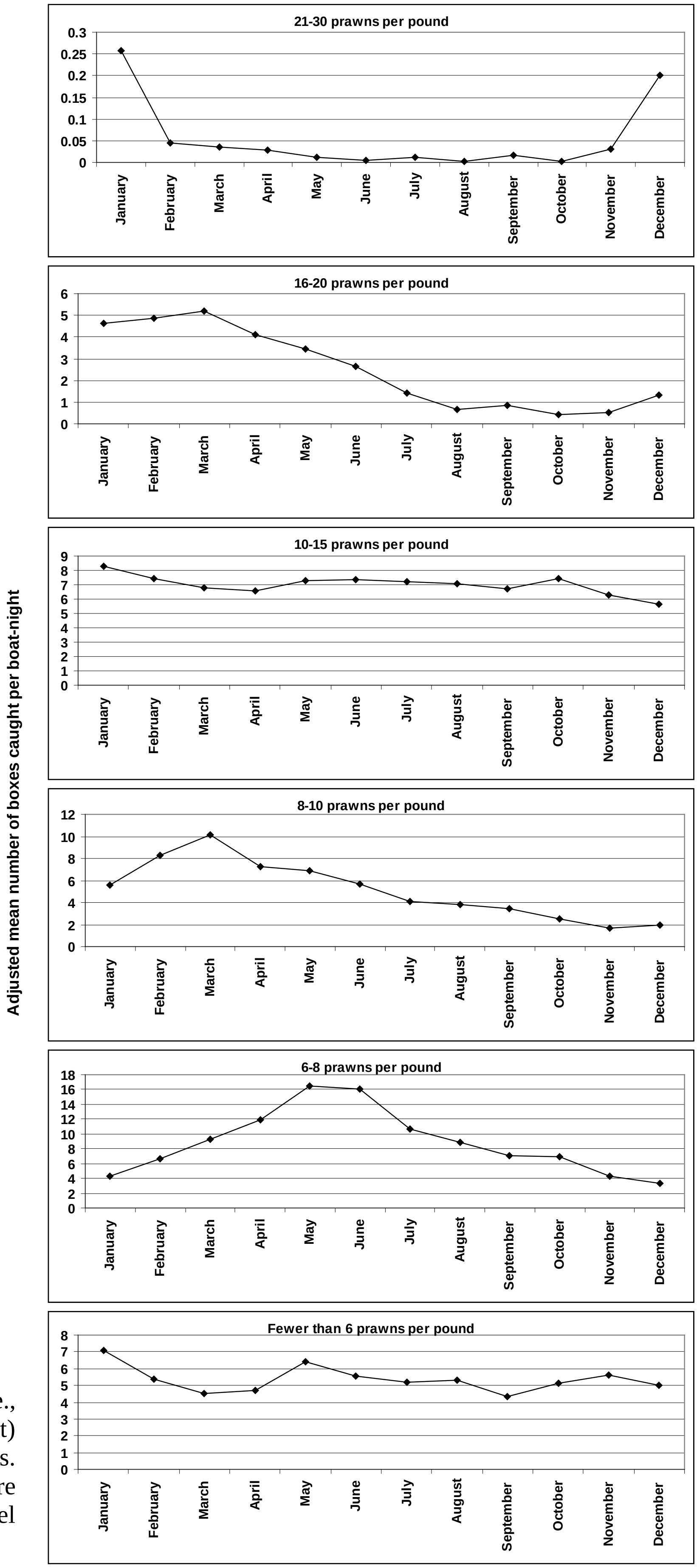


Figure 15-9. Adjusted catch rate (i.e., number of 5 kg boxes per boat-night) for six commercial prawn size grades. The adjusted mean catch rates are derived from the Poisson model presented in Table 15-7.

15.4.4 Logbook catch and effort data

Logbook data were examined for the region between 21°S and 26°S on the Queensland east coast, which encompasses the northern section of the EKP fishery from Fraser Island to the Swain Reefs. This region also encompasses the Queensland saucer scallop trawl fishery and some care is required to separate the catch and effort statistics for each sector. For the majority of the catch and effort data, the targeted daily effort for an individual vessel is obvious from the database records. However, there can be some uncertainty determining which species the fisher is targeting when more than one species is recorded in the catch. To address this, the daily catch of each species group was converted to dollars by multiplying the catch weight by the price (i.e., $16 per kg for EKP and $20 per kg meat weight for scallops). Targeted effort for a given boat-day was then determined based on the species with the highest catch value.

Effort in this part of the fishery ranged between a maximum of 10,922 boat-days in 1992 and a minimum of 5608 boat-days in 2011 (Figure 15-10). (Note: data from 1988 were excluded as this was the first year of the mandatory logbook program and it is widely considered that not all catch and effort were accounted for in the first year). Nominal annual effort declined from about 10,000 boat-days in 2002-2004, to about 6000 boat-days in 2008-2011. Reported annual landings of EKP in the region peaked in 2009 at 1518 t, with a similar peak of 1497 t in 2003. In general, catch increased from 1988-2003, but has declined in recent years from 2009 to 2011 to about 887 t.

Annual scallop trawl effort was consistently greater than EKP effort in the 1990s, and frequently above 12,000 boat-days, but declined markedly following the introduction of the Trawl Fishery Management Plan in 2000 (Figure 15-10). The Plan resulted in many trawler operators leaving the industry, especially vessels that were comparatively small and/or had relatively few allocated boat-days. The decline in scallop effort is particularly marked from 2000 to 2002. From 2002-2011 scallop effort remained comparatively low, peaking at 6739 boat-days in 2004 and falling to a minimum of 3200 boat-days in 2011. Since 2002, EKP annual effort has exceeded scallop effort. The decline in effort following the Trawl Plan introduction was more marked for the scallop fishery than for the EKP sector. This may be due, in part, to differences in vessel sizes in the two sectors. As the EKP sector encompasses deeper, offshore areas, the size of the EKP vessels is generally larger than the scallop fishery. The Trawl Management Plan had a greater impact on smaller vessels that generally fished in comparatively shallow more-inshore areas.

About 1100 boat-days of trawl effort per year in the region are associated with ‘other’ trawled species (Figure 15-10), predominantly banana prawns and bay prawns in shallow inshore areas near Bundaberg and Gladstone.

Monthly catch rates of the EKP fishery increased from 1988 to 2011, especially since the introduction of the Trawl Plan in 2000 (Figure 15-10). In the 1980s and 1990s catch rates generally ranged between 70-110 kg per boat-night. In recent years (i.e., 2009-2011) catch rates have ranged from about 100-330 kg per boat-night. The long-term increase is partially explained by increasing fishing power (see Section 19), in part due to smaller vessels departing the industry, especially after the Trawl Plan introduction. March has the highest mean catch rate, while October has the lowest. The high catch rates in February, March and April are due to the combined effects of a peak in the number of prawns entering the fishery (i.e., recruitment), and growth. These months of high catch rate coincide with the peaks observed for prawns in the 16-20 count per pound and 8-10 per pound grades in Figure 15-9.

The decline in catch rate from March to October reflects the decline in the population size, due to both fishing and natural mortality.

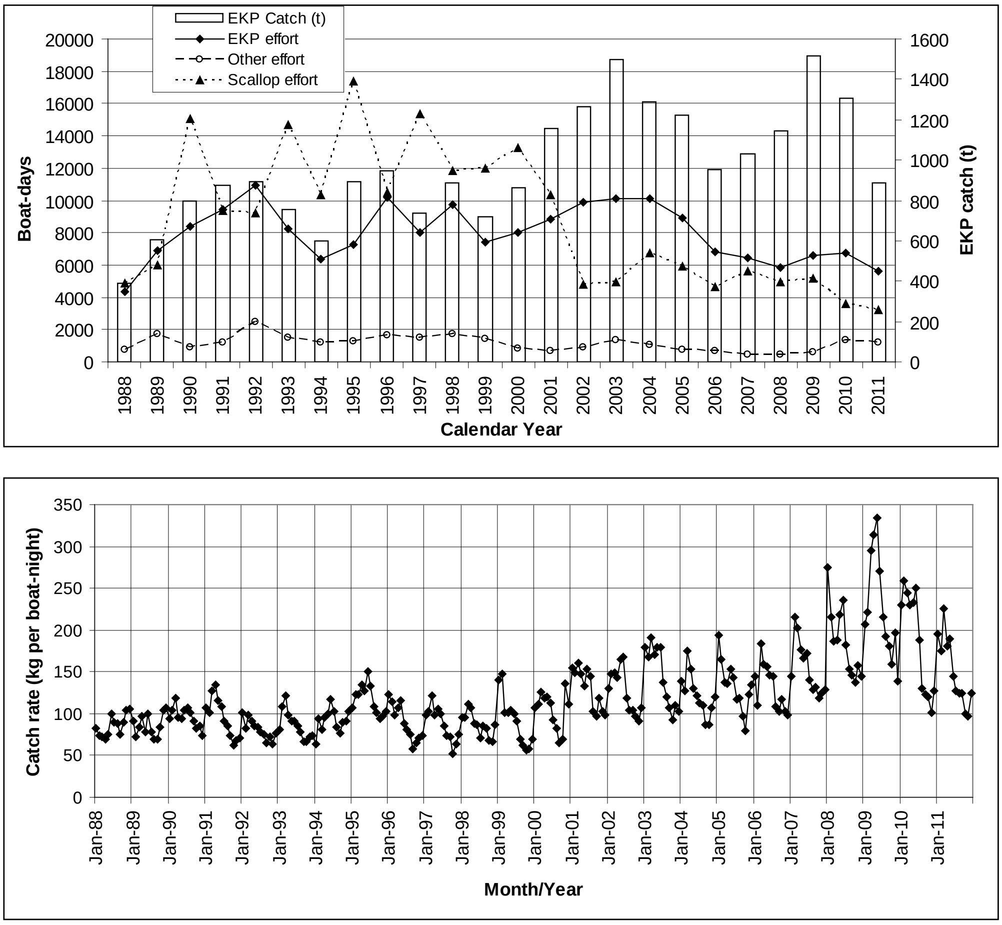


Figure 15-10. Catch and effort trends in the EKP fishery between 21°S and 26°S. The Queensland saucer scallop fishery also occurs in this region. The upper graph shows annual effort in the EKP, scallop and 'other' minor sectors in the area, as well as EKP landings (in tonnes). The lower graph shows monthly EKP catch rates.

The spatial distribution of the EKP catch data north of Fraser Island, based on six minute grid sites, indicates negligible catches west of the Capricorn-Bunker Islands between Gladstone and Bundaberg (Figure 15-11). Although there is considerable trawl effort in this area targeting banana prawns in shallow inshore waters and scallops further offshore, negligible EKP catches are reported. This suggests that EKP caught north of about 24°S are unlikely to recruit from adjacent coastal nursery areas, such as estuaries and inshore seagrass areas. The logbook data support the hypothesis that, in their northern-most distribution, juvenile EKP utilise shallow offshore reefs within the Capricorn-Bunker Islands as nursery areas, and that they move east-northeast as they grow and recruit to the fishery.

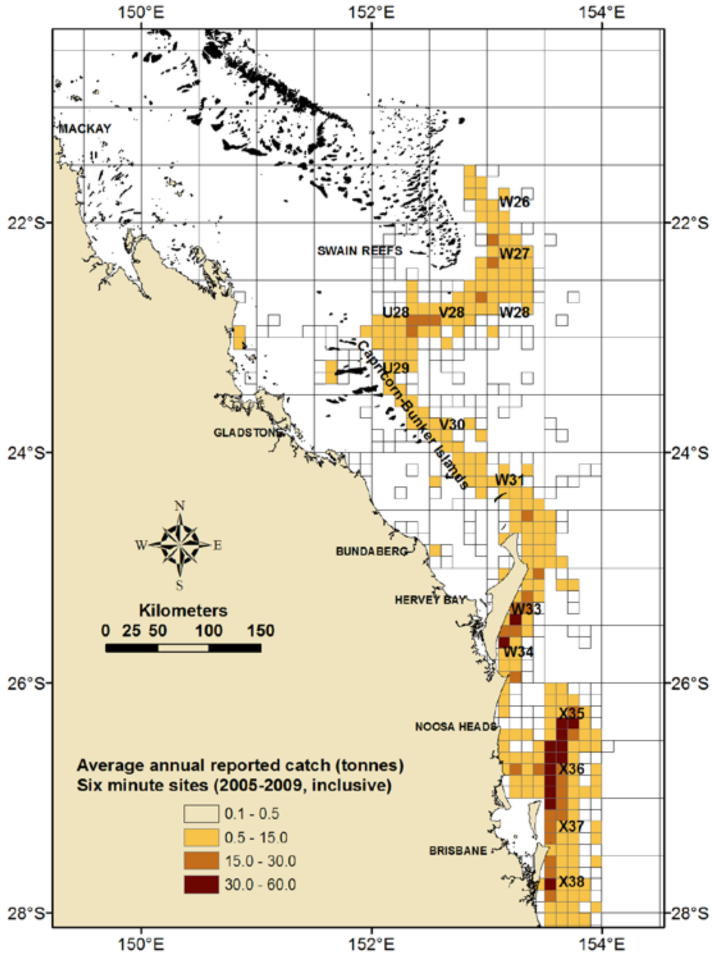


Figure 15-11. Spatial distribution of the eastern king prawn catch in Queensland based on six minute grid sites, from the Queensland CFISH logbook database. As there is negligible catch reported west of the Capricorn-Bunker Islands, it seems unlikely that the prawns recruit from adjacent coastal nursery grounds. These data are consistent with the prawns utilising offshore reefs associated with the Capricorn-Bunker Islands as juvenile nursery grounds, and migrating east-northeast to fishing grounds. Data for Moreton Bay (near Brisbane) are omitted because of the multispecies nature of landings from the Bay making it difficult to quantify the EKP catch.

15.5 Discussion

15.5.1 Tagging studies

Prawns tagged off Fraser Island moved significantly shorter distances than those tagged near North Reef - adjusted mean distances for the North Reef prawns were almost twice that of Fraser Island prawns. As none of the Fraser Island prawns were caught north of the island (Figure 15-4), the results suggest that EKP from the shallow areas around Fraser Island, which are thought to recruit from the Great Sandy Straits (i.e., the area between Fraser Island and the mainland) via the Wide Bay Bar, probably contribute very little to catches north of about 24^{o}S.

Recapture rates of Fraser Island tagged prawns were very low and less than half that of the North Reef prawns (Table 15-4). This could be due to a a) lower exploitation rate, b) lower reporting rate by fishers, and/or c) higher mortality rate, for tagged prawns at Fraser Island compared to North Reef. Interestingly, the average time-at-liberty was significantly less for the Fraser Island prawns. This is difficult to explain as it can also be indicative of a comparatively high exploitation rate (and yet the proportion recaptured at Fraser Island was lower than North Reef). The comparatively brief time-at-liberty for the Fraser Island prawns may be indicative of movement out of/away from trawled areas. Hence, while the prawns remained in Fraser Island coastal waters they were caught relatively quickly, but once they moved away (possibly northward), they were not recaptured and/or not reported. It is possible that the Fraser Island prawns moved significant distances northwards, but their recaptures were not reported. Project staff were aware that some fishers did not support the tagging study and that they were unlikely to report recaptures.

Previous EKP studies in the 1990s also showed that very few prawns tagged at Fraser Island and more southern locations including Moreton Bay and New South Wales, contributed very little to catches north of Fraser Island (Figure 15-12). In neither the recent (2009) nor past 1990-1991 Fraser Island tagging experiments were prawns recaptured north of the Island. Both present and past studies suggest that the northerly migration of Fraser Island prawns may be diminished or halted. It is noteworthy that the 1990-1991 tagging also found a small proportion of prawns from Moreton Bay migrated north of Fraser Island (green trajectories Figure 15-12).

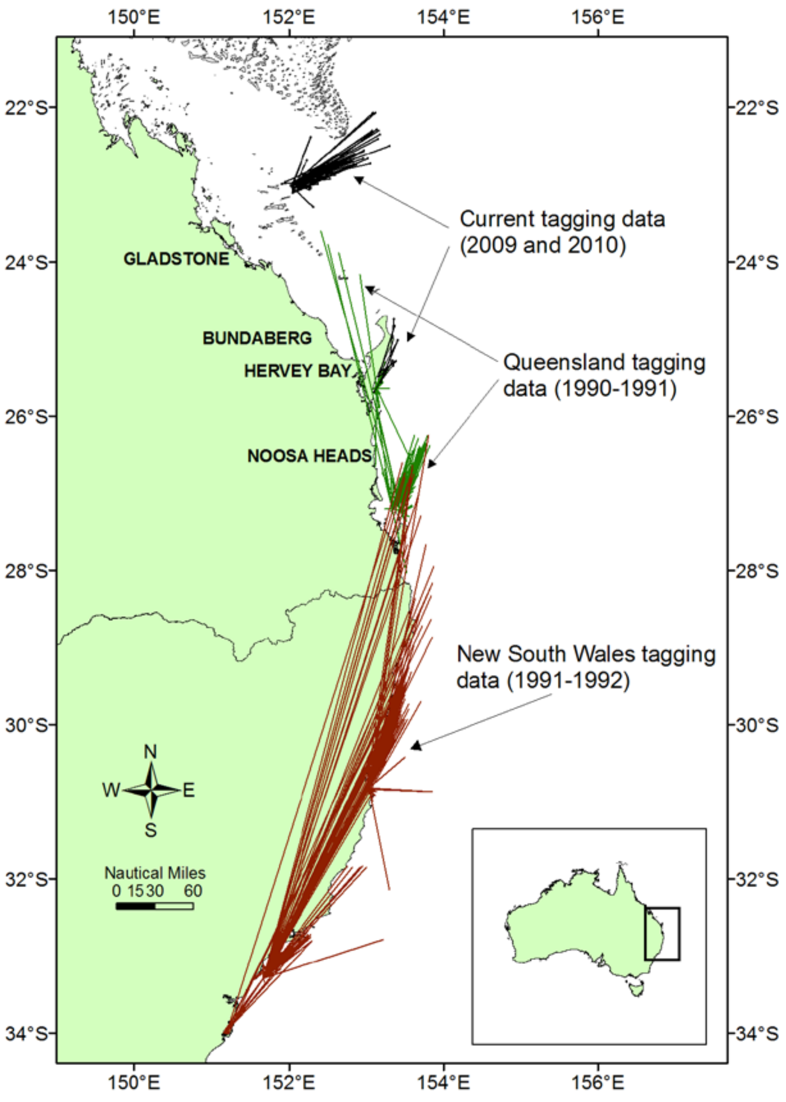


Figure 15-12. Summary of EKP tagging experiments in New South Wales and Queensland in the 1990s and the recent experiments in 2009 and 2010. The lines show the release and recapture points for each prawn. Note the lack of Fraser Island tagged prawns recaptured north of the Island.

15.5.2 Length-frequency analyses

MDS of the length-frequency data from the 83 sampling sites indicated that three general areas could be discerned, based on the prawn size classes. As the Fraser Island sites produced the smallest prawns (Figure 15-5), results from the sampling program support the idea that the Fraser Island region is a major source of recruits, via the Wide Bay Bar. While these prawns almost certainly make up the majority of catches in the Fraser Island area, the proportion that migrate northward and contribute to catches between Fraser Island (25ºS) and the Swain Reefs (21ºS) is unknown. Results from the tagging studies discussed above suggest this proportion is likely to be low (i.e., less than about 5%).

So where do the prawns that make up catches in the northern part of the fishery (i.e., 22ºS-24ºS) come from?

The spatial origins of the prawns that comprise the North Reef intermediate length-frequency distribution (Figure 15-6) remain unknown, but it seems likely the majority utilise shallow offshore reefs in the Capricorn-Bunker Islands as nursery grounds. The tagging results suggest that the North Reef prawns were probably migrating from the reefs in an east/north-easterly direction when they were sampled and tagged. After being released, they appear to have continued their migration to deeper (i.e., 100-250 m) grounds further offshore, such as the Swain Reefs, where they are caught by the fleet. We trawl sampled in shallow areas (i.e., 30-70 m) near North Reef during the 2010 charter (Figure 15-2), and to a lesser extent during the 2009 charter, in an attempt to demonstrate that prawn abundance declines with increasing distance from the reefs. However, sampling in these grounds was difficult as the area is largely untrawled and challenging to skippers. Catches were associated with large amounts of sponge bycatch with few or no EKP. We cannot, therefore, conclude with certainty that the origin of North Reef prawns is shallow offshore reefs, however, we suspect this to be the case, and that the majority of the commercial catch in this area (i.e., 21ºS-24ºS) originates from reefs in the Capricorn-Bunker Island group. This is partially supported by the recent findings of an undergraduate student from the University of Queensland who sampled juvenile EKP on Heron Island (i.e., one of the Capricorn-Bunker Islands) intertidal reef flats (Cameron Cotterell, pers. comm.).

It is noteworthy that a closely related species, the red spot king prawn, *M. longistylus*, which is also targeted by trawlers further north on the Queensland coast, has a juvenile phase which is restricted to shallow offshore reef flats (Courtney and Dredge 1988; Dredge 1990). The use of offshore reefs as nursery grounds by *M. plebejus* may be an adaptation by the species in its northern distribution, which spatially overlaps with the Great Barrier Reef. Use of reefs may also reflect a vestigial migratory behaviour from thousands of years ago during previous ice ages when the sea level was significantly lower than present and the Capricorn-Bunker Islands formed part of the Australian coastline.

15.5.3 Trends in grading data

Although it is a valuable dataset, it is important to note the grading data analysed were from only one company (albeit five vessels) who operate predominantly in a few 30 minute grids in the far-northern part of the fishery. Hence, the data may not reflect the recruitment dynamics for the whole fishery. Nevertheless, the trends can be used to infer useful information on the population dynamics, including recruitment, growth and movement.

The adjusted mean catch rate of the smallest grade (i.e., 21-30 prawns per pound or 15-22 g) peaked in December and January (Figure 15-9). Although this grade made up only a very minor component of the company's catch, the peaks reflect when prawns first recruit to the fishing grounds in this region. The results are consistent with the timing of recruitment in Moreton Bay (Courtney *et al.* 1995) and offshore waters in southeast Queensland. The March peak in adjusted catch rates for slightly larger size classes (i.e., 16-20 prawns per pound or 23-29 g) is the product of both a) numbers of prawns entering the fishery peaking, and b) growth of the prawns that first started to recruit in December and January. The May-June peak in adjusted catch rates for the 6-8 prawns per pound category (i.e., weighing 56-75 g), is also consistent with recruits entering the fishery in December and January and continuing to grow to this larger grade over the summer and autumn months. By October-November, catch rates for most grades, especially small grades, have declined to a minimum (Figure 15-9) – consistent with the population declining to an annual minimum at this time. Interestingly, catch rates in the 10-15 prawns per pound grade (i.e., 30-44 g), and the very large prawns (i.e., fewer than 6 prawns per pound grade or > 76 g), showed little seasonal variation.

15.5.4 Logbook data and recruitment

The lack of EKP catch and effort data between the Capricorn-Bunker Islands and the coast (Figure 15-11) strongly suggests that *M. plebejus* do not utilise inshore habitats in this part of the fishery. Therefore, those prawns that make up the commercial catch in the northern part of the fishery must largely recruit from either 1) Fraser Island and areas south including Moreton Bay and New South Wales, or 2) offshore reefs in the Capricorn-Bunker Islands. As the previous (i.e., 1990s) and recent (i.e., 2009) tagging experiments indicate extremely few prawns from Fraser Island or more southern areas, contribute to the northern part of the fishery, the origins of the prawns appears to be shallow offshore reefs.

If we assume the peak in commercial catch rates is indicative of recruitment, then we can conclude that recruitment in the northern part of the fishery peaks in March (Figure 15-10), although catch rates are comparatively high in January, February and April. The actual numbers of prawns entering the fished population probably peaks in January-February, while high catch rates in March and April are sustained by the increase in weight due to growth, even though the actual number of prawns is probably starting to decline then. The decline in population size, based on the catch rate trends, is apparent and consistent from March-October.

In summary, the recruitment dynamics of EKP in their northern distribution between 22^{o}S and 24^{o}S appears largely dependent on prawns migrating off shallow offshore reefs within the Capricorn-Bunker Group, rather than from adjacent inshore nursery habitats. This is unusual and has not been reported before for *M. plebejus*, although it is normal for another closely related species. The timing of recruitment is consistent with other parts of the fishery, where peaks in abundance of very small size classes (i.e., 5-10 g) occur in October-November in the comparatively shallow, inshore waters of Moreton Bay where depths do not exceed 35 m (Courtney *et al.* 1995). In December-January catch rates of the smallest commercial grade reported (i.e., 21-30 prawns per pound, or 15-22 g) peak in the fishery, while catch rates of next largest size grade (16-20 prawns per pound, or 23-29 g) peak in March. These temporal and spatial patterns in recruitment should be considered by the fishery managers and stakeholders when attempting to maximise value from the fishery and reduce growth overfishing.

16 Appendix 4. Economic survey of the eastern king prawn fishery (Objective 2)

This section addresses Objective 2 *Undertake an economic analysis of the eastern king prawn fishery and determine the optimum yield and effort for profitability.*

16.1 EXECUTIVE SUMMARY

An economic analysis of the Queensland eastern king prawn (EKP) trawl fishery is presented based on data obtained from a voluntary economic survey of commercial fishing for the 2007/08 financial year. The survey was undertaken by *Fisheries Queensland* to collect updated data related to the cost of operating a commercial fishing business. This included asking fishers about their fixed and variable costs, as well as information regarding the level of capital invested in the business. The response rate to the survey was low and so when the current project (i.e., FRDC project 2008/019) commenced in 2009, additional EKP fishers were asked to participate. In total, 24 EKP fishers provided data on their costs. Income estimates were derived using logbook for 26 vessels and seafood price data. Following are the key findings. These data were used in the bio-economic modelling of the EKP fishery reported elsewhere in the report.

1. *Average Fixed Cost (AFC)* for a license holder working in the Queensland EKP fishery was $41,323 for the 2007/08 financial year.

2. *Average Variable Cost (AVC)* was $318,849 for 2007/08 financial year.

3. *Average Invested Capital (AIC)* for 2007/08 was $782,264 per license.

4. *Average Depreciation* (includes only primary vessel and electronics) was $25,901 per licence for the 2007/08 financial year.

5. *Average Labour Cost* per license was $148,323 for 2007/08, based on a total of 64 employees reported among the surveyed license holders. The average number of employees per license was 2.7. This labour cost estimate is generally considered to be high, probably because some survey participants included shore-based staff (i.e., office administration and workshop staff) in their reported labour costs.

6. *Average Gross Value of Product (GVP)* was estimated using the Fisheries Queensland logbook data for 26 EKP fishers averaged over a 4-year period (2005-2008 calendar year). Average annual GVP was $378,674. The average annual GVP for the 26 vessels combined was just under $10 million.

7. *Average Boat Gross Margin (BGM)* was $59,825 for 2007/08.

8. *Average Boat Operating Surplus (BOS)* for the 2007/08 financial year was $18,502.

9. *Gross Returns Index (GRI)* for the 2007/08 financial year was 105.14 per license.

10. *Total Vessel Cost (TVC)* was estimated as the sum of the average fixed and variable costs, and labour costs, to be $508,495 for 2007/08.

11. *TVC compared to GDP*. When average TVC of $508,495 was subtracted from the average GVP of $378,674, an average annual loss of $129,821 was obtained per license.

The logbook data indicate that the 26 vessels that were used to estimate GVP land about $10 million of product annually, with about 98% of the catch value attributed to eastern king prawns. Given that the Queensland fishery lands about $30 million annually of EKP, the sample size accounts for about one-third of the fishery's total landings. As there are about 200 vessels operating in the Queensland EKP fishery, the results suggest that the survey participants were probably from more powerful or more efficient vessels, or were better skippers, than average license holders. Despite the resulting relatively high average annual GVP of $378,674, the total vessel cost (TVC) still exceeded GVP by $129,821 (i.e., an average loss per license). This is likely due, in part, to the high labour costs (i.e., $148,323 per license) reported by some license holders during the survey. If we chose an alternative labour cost estimate, e.g., based on 28% of average GVP (i.e., 0.28 x $378,674), the average labour cost is reduced by about $42,000 to $106,029. While this substantially lowers the labour cost estimate, it is still not enough to prevent TVC from exceeding GVP, hence indicating that for an average license holder, the fishery is not economically viable.

16.2 INTRODUCTION

The collection and analysis of commercial fisheries' economic data are required for setting economic efficiency and profitability management objectives. Previous economic studies of Queensland fisheries include those of Moxon and Quinn (1984) who examined the trawl fishery in southeast Queensland, and Reid and Campbell (1999) who evaluated the impacts of closing the Queensland beam trawl fishery. Taylor-Moore *et al.* (2000) undertook an economic analysis of all commercial fishing sectors in Queensland for the 1997/98 financial year. At the time there were approximately 1900 commercial trawl, line, net and crab licenses in Queensland.

In 2009 Fisheries Queensland initiated another economic survey of the state's commercial fishing licence holders for the 2007/08 financial year. One of the objectives of the study was to compare results against those of Taylor-Moore *et al.* (2000), effectively commenting on economic performance over a 10-year period. The study was based on a survey (copy of the survey can be obtained from J. Maroske or A. Courtney, DAFF) which was posted to all Queensland commercial fishers who were asked to provide information on the fixed (i.e., capital, license, wharfage, insurance, etc.) and variable (labour, fuel, maintenance) costs associated with each commercial sector (i.e., trawl, net, line and crab). Spatial information on seafood sales and port usage were also sought to determine how the regional distribution of fishing businesses has changed. The survey also sought details on the number of years each licence holder worked in the industry, vessel characteristics and issues that fishers felt were important to the industry. The survey was forwarded to all 1317 Queensland licence holders. Disappointingly, only 103 responses were received (i.e., < 10%) which significantly reduced the value of the data. Results from the survey are presented in the Fisheries Queensland report "Economic survey of Queensland commercial fishers for financial year 2007-08".

A total of 19 otter trawl licence holders responded to the survey. Of these, 14 were identified as primarily targeting Eastern King Prawns (EKP), and therefore their data were deemed highly relevant to the current bioeconomic EKP study. On closer examination of the data, however, only 12 of these vessels provided adequate information. To increase the sample size, project staff obtained completed surveys from an additional 12 EKP fishers in 2010, bringing the number of licence holders who provided data to 24. All survey data relate to the 2007-08 financial year. Logbook records indicated that these 24 participants contributed about 20% of the total annual catch and effort in EKP fishery.

16.3 RESULTS

16.3.1 Invested Capital

Invested capital refers to items that are normally required by the commercial licence holder to effectively run their business. Most of these are only purchased once and rarely replaced. Survey respondents were asked to provide current (i.e., 2007-08) market value estimates for the capital items that they owned and used as part of their business. Table 16-1 shows a breakdown of the invested capital for the 24 licence holders for the 2007-08 financial year.

Table 16-1. Invested capital spending behaviour in the Queensland EKP fishery, based on survey results from 24 licence holders. Note that some survey respondents provided no data for some items. Averages include zero values and where a fisher provided no data, a zero value was assumed. This is likely to result in low average value estimates.

Invested Capital Item	**Total Invested Capital ($)**	**Average Invested Capital ($)**	**Invested Capital (%)**
Licence package (broker's estimate)	3,116,770	129,865	16.60
Primary boat hull	10,769,573	448,732	57.36
Electronics	1,663,000	69,292	8.86
Jetty/Berth/Mooring	280,600	23,383	1.49
Sheds	485,000	420,208	2.58
Cold rooms, freezers etc. on boat	438,000	18,250	2.33
Cold rooms, freezers, etc. on shore	352,200	14,675	1.88
Packing equipment - on shore	325,000	13,542	1.73
Trailers	21,500	896	0.11
Trawl gear	559,000	23,292	2.98
Net gear	96,000	4000	0.51
Other	160,000	6667	0.85
Vehicles	507,700	21,157	2.70
TOTAL	**18,774,343**		**100**

The average invested capital was $782,264 (i.e., $18,774,343 divided by 24) per licence holder. The largest component of capital investment was the primary boat hull which accounted for 57.36% of the total. The licence package was the next highest item at 16.60%. This is noteworthy given that fishery effort units, which make up most of the license package cost, currently have a low value (i.e., < $10 per effort unit). The next three largest capital investment costs were electronics (8.86%), trawl gear (2.98%), vehicles (2.70%) and sheds (2.58%). The remaining items contributed little to invested capital.

16.3.2 Depreciation

Depreciation is the annual reduction in the value of invested capital items that are required for running the business. These items depreciate over time due to either general 'wear and tear' or ageing. We used a depreciation rate that was applied to the combined value of the primary boat hull and electronics to give a single value for the vessel, consistent with the Taylor-Moore *et al.* (2000) study. This value was then multiplied by the appropriate prime cost depreciation percentage that was sourced from the Australian Taxation Office website. The depreciation rate for fishing vessels (including trawlers) longer than 10 meters was based on a period of 20 years (listed as 48100–48200 of taxation ruling) effective July 2009 (i.e., an annual depreciation rate of 5%). The depreciation rate of navigational aids and communication assets is generally higher and based on a 5 year period (i.e., 20% annual depreciation). The annual depreciation of all 24 licence holder vessels and their average depreciation are provided in Table 16-2.

Table 16-2. Yearly depreciation rate for Queensland EKP fishery vessels.

Depreciation Item	Total depreciation all 24 vessels	Average annual depreciation per vessel
Primary boat hull and electronics	$621,629	$25,901

16.3.3 Fixed Costs

Fixed costs are defined as those costs that remain "fixed" from one year to the next, regardless of the level of fishing activity or output of the individual commercial licence holder. As such, they are independent of production. A breakdown of the fixed costs for the 24 licence holders for the 2007-08 financial year is provided in Table 16-3.

Table 16-3. The fixed costs for 24 licence holders in the Queensland EKP fishery in the 2007-08 financial year. Note that some survey respondents provided no data for some items. Averages include zero values and where a fisher provided no data, a zero value was assumed. This is likely to result in low average value estimates.

Fixed Cost Item	Total Fixed Costs ($)	Average Fixed Costs per vessel ($)	Percentage Fixed Costs (%)
Leasing costs	125,655	5236	12.67
Motor vehicle fees	18,759	782	1.89
Banking charges	9329	389	0.94
Overdraft interest, interest on loan	83,280	3470	8.4
Port, jetty, etc. charges	76,866	3203	7.75
Licence and industry fees	121,885	5079	12.29
Insurance costs	419,177	17,466	42.27
Other boat fees	14,020	584	1.41
Meetings, travel etc.	57,619	2401	5.81
Other expenses	65,172	2716	6.57
TOTAL	**991,762**	**41,323**	**100.00**

The total fixed costs for the 24 licence holders for the 2007-08 financial year was $991,762 with an average of $41,323 per vessel. The largest fixed cost was insurance which accounted for 42.27% of the total, followed by leasing (12.67%) and license and industry fees (12.29%). The remaining fixed costs were relatively minor.

16.3.4 Variable Costs

Variable costs refer to the day-to-day operational costs associated with fishing and include steaming, trawling, packaging and other consumable costs. Variable costs are largely dependent on the level of fishing effort and fluctuate accordingly (Table 16-4). For the EKP fishery licence holders surveyed the variable costs were 7-8 times higher than fixed costs (Table 16-3) for the 2007-08 financial year. The average annual variable costs were $318,849 per vessel with fuel accounting for 61.13% or an average of $194,924 per vessel. This is the gross fuel cost and includes the 10% GST and the fuel excise of $0.3814 per litre that primary producers can claim back from the Australian Taxation Office. In September 2007 the price of fuel was $1.36 per litre and by June of 2008 it had risen to $1.81 per litre (prices include GST and the excise), illustrating the variability and potential impact that fuel prices have on the fishery. Repairs and maintenance accounted for 21.43% of variable costs with an annual average of $68,329. The remaining 14 items contribute little to the variable costs.

Table 16-4. Variable costs reported by 24 licence holders in the Queensland EKP fishery for the 2007-08 financial year.

Variable Cost Item	Total Variable Costs ($)	Average Variable Costs ($)	Percentage Variable Costs (%)
Fuel	4,678,174	194,924	61.13
Oil and grease	23,019	959	0.30
Gas	16,845	702	0.22
Ice	4000	167	0.05
Chemicals	41,068	1711	0.54
Food for crew	143,979	5999	1.88
Office consumables	7,499	312	0.10
Electricity	58,582	2441	0.77
Communications	107,302	4471	1.40
Packaging	223,424	9309	2.92
Vehicle running	108,593	4525	1.42
Repairs and maintenance	1,639,894	68,329	21.43
Purchase major items	323,000	13,458	4.22
Fishing equipment	132,709	5530	1.73
Marketing	134,927	5622	1.76
Other	9,369	390	0.12
TOTAL	**7,652,284**	**318,849**	**100.00**

16.3.5 Labour Costs

Labour costs refer to the wages, superannuation contribution, workers compensation, training and other employee-related expenses (Table 16-5).

The average labour cost per licence holder for the 2007-08 financial year was $148,323, which was distributed across an average of 2.7 employees per licence holder. The average cost of labour per employee was $55,621. There was uncertainty associated with this estimate mainly due to the inclusion of company-based licence holders in the survey respondents who included land-based staff (i.e., administration, workshop staff, etc.) in their employee list. This has likely increased total labour costs. It is also noteworthy that under some business models, there can be more than one crew per vessel. For example, some businesses with more than one vessel require crew to spend five weeks at sea followed by two weeks recreation/leave. When the first crew return to port after five weeks, the vessel is quickly redeployed back out to sea with a second crew for another five week period. Hence, a vessel associated with a single license may have more than one crew, hence increasing the number of employees per licence or per vessel. An alternative approach for estimating labour costs is to assume that crew are paid a percentage of the total reported catch value (Punt *et al.* 2010)

Table 16-5. Labour costs provided by 24 licence holders in the EKP fishery for the 2007-08 financial year.

Total labour costs	**Average labour costs per licence holder. Up to six employees employed per license**	**Total employees**	**Average number of employees per vessel**
$3,559,744	$148,323	64	2.7

16.3.6 Gross Value of Production (GVP)

GVP was estimated as the product of the catch as reported in the logbook database and the price per kilo of product. Obviously, these estimates are very much influenced by the accuracy of the reported logbook and price data. Price also varies with demand, season, grade/size and whether the product is cooked.

Although the survey sought economic data from fishers for one financial year (i.e., 2007-08), the mandatory logbook database provides a much longer time series of reported catch, and hence GVP. For this reason, GVP was derived using the reported logbook catch data for the surveyed licence holders averaged over a recent four-year period (i.e., 01/01/2005-31/12/2008). A recent average annual estimate of income is likely to be more representative than a single value for the 2007-08 financial year. Also, catch data from two additional licence holders who did not participate in the survey, but who allocated almost all of their effort to the EKP fishery were also used. Hence, average annual GVP was derived using a sample size of 26 licence holders.

A summary of the reported catch for the 26 vessels is provided in Table 16-6. Eastern king prawns are the main target species in the fishery and made up 97.49% of the total catch weight. Additional income to fishers is provided by Balmain bugs, Moreton Bay bugs, scallops and Champagne lobsters. The average annual catch of EKP per vessel was 22,776 kg.

Table 16-6. Average reported annual catch for the 26 vessels.

Catch component	Average annual catch (kg) (all 26 vessels)	Average annual catch per vessel (kg)	Percentage Catch (%)
Balmain Bug	10,271	395	1.69
Moreton Bay Bug	1,786	69	0.29
Champagne lobsters	2,470	95	0.41
Prawns	592,179	22,776	97.49
Scallops	742	29	0.12
TOTAL	**607,447**	**23,364**	**100.00**

Catch price data

Information on prices received by fishers for the various components of their catch was obtained from four sources. These were mainly based on receipts issued to fishers by processors who purchased their catch, copies of which were made available to the project. Price list 1 was obtained from one vessel operator for the period July 2006 to July 2009. Price list 2 was obtained from five vessels for the month of May 2010. Price list 3 was obtained from one vessel for the period March 2009 to October 2009 and price list 4 was obtained from 11 vessels from various periods between 2006 and 2010. The prices are presented in Table 16-7 which also includes averages for the four lists.

Table 16-7. Prices paid to EKP fishers ($/kg) for their reported logbook catches.

Species	Price list 1	Price list 2	Price list 3	Price list 4	Average
Balmain Bugs	10.25	11.00	9.00	10.08	10.08
Moreton Bay Bugs	21.1	18.50	12.50	17.36	17.37
Champagne Lobsters	11.25	16.00	11.50	12.92	12.92
Prawns	16.14	16.03	16.65	16.49	16.33
Scallops	13.49	13.49	13.49	13.49	13.49

In general, there was relatively little variation between price lists. The largest variation was associated with Moreton Bay bugs, which may be attributed to prices received for small, medium and large size classes. Given that bugs contribute only a minor component of the catch (Table 16-6), the variation is unlikely to be influential in any bioeconomic modelling. Price also varies considerably with different sizes/grades of prawns, although this is not reflected in the data here. The price of $16.33 per kg should be considered as the average paid for the 'average' size category, with smaller categories commanding lower prices, and larger categories commanding higher prices.

Total annual GVP for the 26 licence holders was $9,846,759.55 (Table 16-8) based on the product of their average annual reported catch from 2005-2008 (Table 16-6) and the average price paid to fishers (Table 16-7). Given that the total annual Queensland EKP catch value is about $31 million, this suggests that the sample of 26 license holders land approximately 30% of the total Queensland EKP catch. This is a relatively high proportion and probably indicates the sample was biased by more powerful and more efficient vessels, and possibly by more successful fishers. The average GVP per vessel (or license) was $378,674. The prawn catch, which was almost entirely comprised of EKP, made up 98.2% of the catch value.

Table 16-8. Gross value of product (GVP) for 26 licence holders in the EKP fishery based on the average price ($/kg) multiplied by average annual landings (kg). Average GVP per vessel is also provided.

Catch component	Average annual catch per vessel (kg)	Average price ($/kg)	Total sample GVP ($)	Average GVP per vessel ($)	Percent of income (%)
Balmain Bug	395	10.08	103,531.68	3983	1.1
Moreton Bay Bug	69	17.37	31,022.82	1198	0.3
Champagne lobsters	95	12.92	31,912.40	1227	0.3
Prawns	22,776	16.33	9,670,283.07	371,875	98.2
Scallops	29	13.49	10,009.58	391	0.1
Total	**23,364**		**9,846,759.55**	**378,674**	**100**

Boat Gross Margin
The most basic form of 'profit' is boat gross margin (BGM) which is defined:

- BGM = Total Boat Gross Value of Production – Total Boat Variable Costs

As we do not have access to total costs, we have developed a similar index of profit based on means, whereby:

- BGM = Mean Boat Gross Value of Production – Mean Boat Variable Costs

Given that the mean annual GVP per vessel (A) was $378,674 (Table 16-8) and the mean annual variable cost per vessel (B) was $318,849 (Table 16-4), the average BGM (A-B) was $59,825.

Boat Operating Surplus
Boat Operating Surplus (BOS) is a financial indicator that takes both fixed and variable costs into account. When the BOS is negative, a fishing business is considered to be operating at a cash loss and when the BOS is positive the business is making a cash profit. BOS does not include an imputed value of wages for the owner-operator of the firm, the unpaid contribution of any family to the business, nor an allowance for depreciation, as these are not regarded as 'cash' items. BOS is a result of the actual transactions of the business and reflects the variations in cash receipts and cash costs. It should be considered a gross concept and not an estimate of the real cost of running the fishing business because skills of the owner-operator and family are not taken into account. BOS is defined as follows:

- BOS = Total Boat Gross Value of Production – Total Boat Cash Costs

Again, as we only have access to mean values, we have developed a slightly different index:

- BOS = Mean Total Boat Gross Value of Production – Mean Total Boat Cash Costs

Given that mean total boat gross value of production (A) was $378,674 (Table 16-8) and the mean total boat cash costs (B) was $360,172 (i.e., mean annual fixed costs Table 16-3 of $ 41,323 plus mean annual variable costs $318,849 (Table 16-4) the BOS (A-B) was $18,502.

Gross Returns Index

Another measure that relates to net cash flow is the Gross Returns Index (GRI). This index describes the relationship between cash income and cash expenditure for a fishing business and measures the net cash return for each $100 cash spent by the licence holder in their fishing activities. GRI is primarily used for comparative purposes and is defined as follows:

- Gross Returns Index = (Total Gross Value of Production / Total Boat Cash Costs) * 100

Again, using means rather than total values, we obtain a GRI of 105.14 (i.e., mean total boat gross value of production (A) of $378,674 from (Table 16-8) divided by the mean total boat cash costs (B) was $360,172, multiplied by 100).

Total Vessel Costs (TVC) compared with GVP

The total vessel cost is the running cost of the business, excluding depreciation, and is derived by summing the fixed, variable and labour costs (Table 16-9). The terminology used here is such that costs associated with a vessel are the same as those of a license holder, since one individual license is associated with one specific vessel.

Table 16-9. Average annual total vessel costs ($).

Average Annual Fixed Costs per vessel	**Average Annual Variable Costs per vessel**	**Average Annual Labour Costs per vessel**	**Average Annual Total Vessel Costs**
41,323	318,849	148,323	508,495

Note the average annual TVC is quite high due to the high labour costs (i.e., $148,323, Table 16-5). When mean TVC ($508,495) was subtracted from mean annual gross value of production ($378,674), the annual loss incurred was $129,821.

16.4 CONCLUSION

While a number of economic performance measures suggest the fishery is profitable (i.e., BGM = $59,825, BOS = $18,502, GRI = 105.14), the mean total vessel cost (TVC = $508,495) exceeded annual mean GVP ($378,674). The high labour cost estimate (i.e., $148,323 per license) is a major contributor to this. If an alternative labour cost estimate was used, such as a fixed percentage of 28% of GVP, this annual loss estimate would be reduced, but not enough to be deemed as profitable for an average license holder.

It is interesting to compare the results with a similar survey of South Australia's (SA) Spencer Gulf and West Coast Prawn Fisheries undertaken in 2007/08 (Econsearch 2009), although caution is required due to differences in some performance measures definitions. One large difference is the total boat gross income, which was estimated to be $744,231 per vessel for SA – about twice that of the Queensland EKP vessels (i.e., GVP = $378,674, Table 16-8).

Interestingly, the combined variable and labour costs from both fisheries were similar – $420,034 for SA and $467,172 for Queensland. Fuel costs for SA vessels were $93,586, which is less than 50% of Queensland EKP vessels at $194,924, probably due to the SA vessels fishing fewer nights per year. Depreciation costs were higher for the Spencer Gulf and West Coast Prawn Fisheries at $141,522 compared to $25,901 for Queensland EKP license holders.

The average invested capital of Queensland EKP license holders was $782,264 (Table 16-1). The largest cost items here were the primary boat hull ($448,732; 53.36%) and license package ($129,865; 16.6%). A similar economic measure for SA vessels referred to as the total boat capital, was $5,456,271 (Econsearch 2009). This was comprised of fishing gear (including vessel) and equipment valued at $1,765,646 and the license estimated at $3,690,625. Clearly, this large difference in invested capital between the two states is largely due to the license value – the license value in SA is approximately 28 times that of a Queensland license. In SA the license is valued at 67% of the invested capital, whereas in Queensland the licence is 17% of the invested capital. These large differences in invested capital probably also explain the large differences in depreciation rates.

17 Appendix 5. Bioeconomic modelling of the eastern king prawn (*Melicertus plebejus*) fishery (Objective 3)

This section addresses Objective 3 *Develop (computer) models of the eastern king prawn fishery that evaluate alternative harvest strategies, as identified by the fishery managers and fishers, and provide advice on the efficacy of each strategy in achieving biological and economic management objectives.*

17.1 ABSTRACT

Recently, some Australian fisheries have experienced reduced profits due to increased fishing costs and static landing prices. These economic circumstances have moved fishery management towards more profitable procedures than maximum sustainable yield (MSY). The Australian eastern king prawn was one such fishery. Therefore new methodology was developed for stock assessment, calculation of model-based and data-based reference points and management strategy evaluation. Bioeconomic fishing data was standardised for calibrating a new length-spatial structured operating model. Results were compared against a standard delay difference biomass model. Simulations identified that a) boat numbers had to be reduced to secure more profitable fishing and reduce the risks of overfishing, b) alternative one-month spatial closures did little to improve profitability and c) catch rate reference points were effective for monitoring and management, but not with excessive fishing effort. If current fishing costs remain steady or increase, fishing between 9000 and 20000 boat-days per year will produce higher profit. Decision makers need to consider the uncertainty, assumptions and political views affecting economic yields.

17.2 INTRODUCTION

The eastern king prawn otter-trawl fishery operates along the east coast of Australia in both Queensland and New South Wales State waters (Figure 17-1). The trawl sector harvests in the order of 3000 tonnes of EKP annually with a landed value in excess of $40 million AUD. The State Governments manage their sectors independently and use a range of input controls including limited vessel entry, boat-day/effort-unit allocations, vessel and gear size restrictions, and spatial-seasonal closures. Despite these controls, the fishery contains substantial fishing effort capacity that may not be economically sustainable; about 600 vessels were licensed to fish EKP and other permitted trawl species. In recent years increased trawling and fuel costs have eroded fishing effort and vessel profits.

The reduced economic conditions have now focused industry and management on developing strategies to maximise economic performance, rather than promoting MSY. These economic conditions influenced the Queensland 2010-2011 trawl management review of biological, economic and social objectives (Dichmont *et al.* 2013; Pascoe *et al.* 2013). In order to improve fishing profits, management procedures were discussed considering further effort control and seasonal closures with options for in-season management based on catch rate reference points. For EKP, these new procedural ideas required stock assessment evaluation for future planning and management.

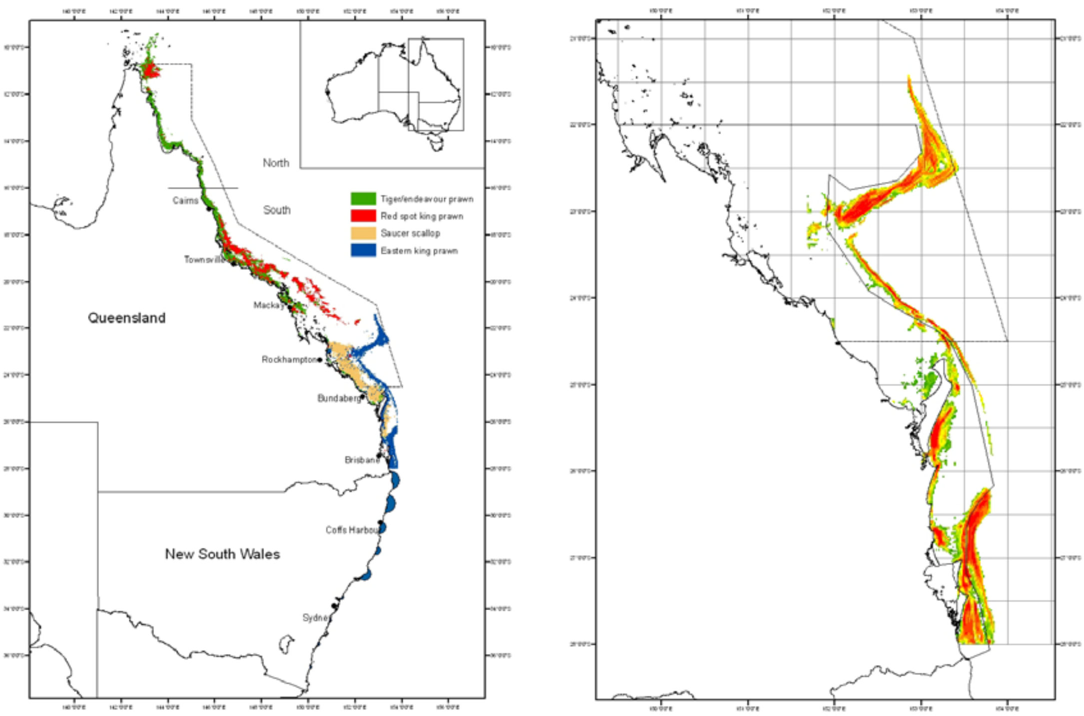


Figure 17-1. Spatial distribution of otter-trawl fishing effort in New South Wales and Queensland waters, Australia. The left map illustrates the different trawl sectors, with the dashed line indicating the Great Barrier Reef world heritage area and the horizontal line at 16°S separating the northern and southern tiger prawn sectors. The right map focuses on the Queensland EKP trawl sector, where red indicates high, yellow medium and green low fishing effort areas, with the solid line below 22°S zoning shallow water depths below 90 m (50 fm). No high resolution vessel satellite data were available to illustrate the New South Wales fishing; bubble plot at 1° latitudes shown on left map.

Since the first assessment of the entire EKP stock by O'Neill *et al.*(2005), which derived an estimate of MSY, the Queensland EKP stock has continued to receive high fishing pressure. This appears to be due to 1) high fuel prices making travel (i.e., 'steaming' time) and fishing less attractive across the state's more northern waters, 2) the close proximity to the scallop fishery (Figure 17-1) whereby fishers can alternate targeting EKP and scallops with relative ease, and 3) the more buoyant prices paid for EKP over tiger prawns, possibly due to their larger attainable sizes. High fishing power increases (≈ 3% year^{-1}) were also integrated within the Queensland fishing effort for EKP (Braccini *et al.* 2012a; O'Neill and Leigh 2007). This has resulted in record harvest levels of EKP in Queensland waters. Also, as EKP migrate north and increase in size (Braccini *et al.* 2012b; Lloyd-Jones *et al.* 2012), Queensland vessels have possibly profited from recent harvest and effort declines in New South Wales (Figure 17-2). Prior to 2005, the New South Wales EKP fishery was assessed as stable (Ives and Scandol 2007). Since then, some NSW vessels have fished for EKP closer to the coast because of higher fuel costs associated with trawling offshore grounds.

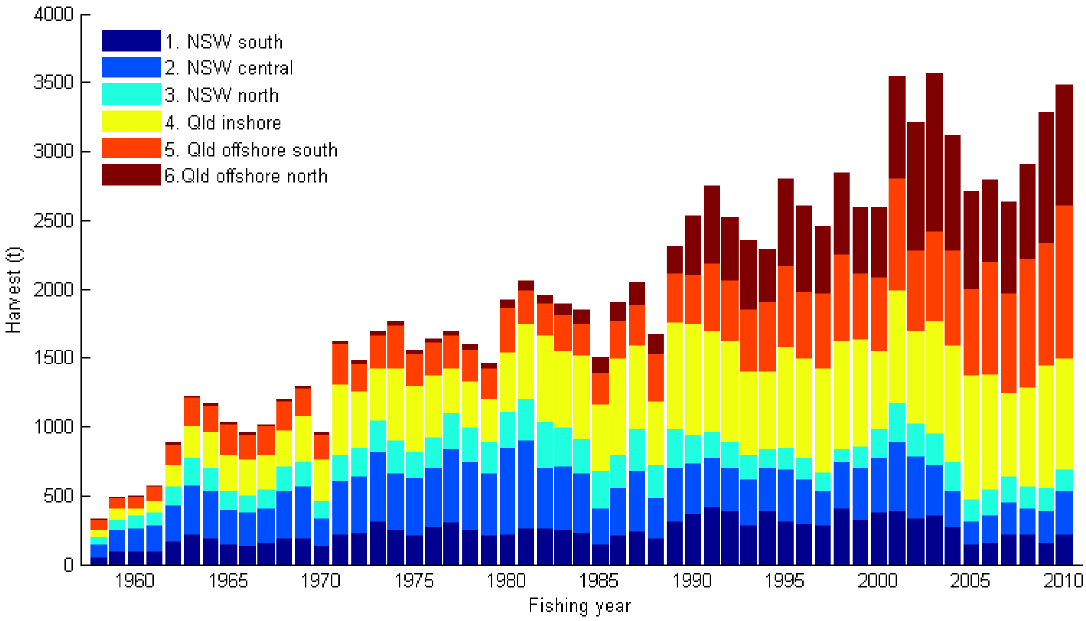


Figure 17-2. Eastern king prawn estimated harvest from New South Wales (NSW) and Queensland (Qld) waters. Regional stratifications are shown in colour.

In order to reassess the fishing pressure on EKP and quantify economic performance, updated reference points were required. Throughout the world reference points have been used as one of the key assessment tools to indicate the state of a fishery. A number of measures, such as simple catch rates or modelled estimates of stock biomass, can be used to set reference points, but developing reference points for a fishery is complex. Their definition is reliant on detailed analyses and their accuracy depends on having reliable data to index population abundance (Hilborn 2002).

For prawn fisheries, the literature contains many examples detailing model-based reference points such as MSY and the corresponding fishing effort for MSY (E_{MSY}). In Australia's Northern Prawn Fishery, they have extended reference points to include vessel-based economics for calculating target maximum economic yields (MEY) (Punt *et al.* 2010). Few empirical (i.e., data-based) reference points have been applied to prawn fisheries. The most notable was South Australia's Spencer Gulf Prawn Fishery, where survey catch rates were used to adaptively change spatial and seasonal closures to match resource availability (Dixon and Sloan 2007). Other prawn fisheries typically used empirical reference points for status reporting only, with no economic consideration or associated management rules. In Queensland, catch-rate-limit reference points were implemented for monitoring EKP in 1999; listed as review events under Schedule 2, Section 8(a), of the Fisheries (East Coast Trawl) Management Plan 1999 (O'Neill *et al.* 2005). They were defined as 70% of the average catch-rate from 1988 to 1997 within specified typical recruitment or spawning months. Further variations on this have evolved, but they all remain invalidated. It was conceivable that they were not related to sustainable stock levels or economics, and no fishing-effort control rules were associated with reference point triggers. In comparison, adaptive quota management procedures using empirical assessments have been successfully applied in non-Penaeid prawn fisheries, some with economic target catch rates based on profitable time periods or surrogates (Little *et al.* 2011; O'Neill *et al.* 2010; Plaganyi *et al.* 2007).

Thus far, there has been no research quantifying economic performance for the EKP fishery, apart from a multispecies analysis focused on the Clarence River and adjacent coastal waters in New South Wales (Ives 2007). Here we evaluated "government-stakeholder" suggested management procedures against model based and empirical reference points for MEY. Simulations using a coupled length-spatial stock and economic model quantified bench marks and boundaries for MSY and MEY management procedures, and optimal fishing seasons. The analyses identified that a) alternate monthly closures provided little to improve profitability or sustainability and b) catch rate reference points were effective for monitoring, but not for management when high fishing effort was available. The study further supported model testing of reference points in fisheries science and highlighted important considerations for economic management. The report represented the success of cross jurisdiction cooperation in assessing the EKP resource along stock boundary criteria rather than political borders.

17.3 METHODS

17.3.1 Data

The EKP data and the length-spatial model were stratified by six offshore fishing regions across New South Wales (NSW) and Queensland (Qld) State waters (17.6 Supplementary Material 1: Model data, Figure 17-20). From south to north the regions were defined and labelled as 1) NSW South (waters south of 30°S), 2) NSW Central (between 29°S and 30°S), 3) NSW North (between 28°S and 29°S), 4) Qld Inshore (< 50 fm water depths, between 21°S and 28°S), 5) Qld Offshore South (>= 50 fm water depths, between 24.5°S and 28°S), and 6) Qld Offshore North (>= 50 fm water depths, between 21°S and 24.5°S latitude). The modelling assessed only EKP recruited to offshore waters and excluded juveniles harvested from estuaries and Moreton Bay. The fishing/biological years were defined and labelled from month November (1) to October (12).

Total catches

The historical harvests of EKP date back to the early 1900's. Early harvests were relatively small (< 200 t) and it was not until the 1950's when the EKP fishery developed. Harvest data from 1958 were assumed for the modelling purposes to represent the commencement of significant fishing mortality (i.e. near virgin state of EKP). Monthly harvests from 1958 to 2010 were reconstructed from four data sources: 1) NSW monthly fisher catch returns from 1900 to 1983, 2) NSW monthly commercial logbooks from 1984 to 2010, 3) Qld annual fish-board records from 1958 to 1980, and 4) Qld daily commercial logbooks 1988 to 2010.

NSW prawn harvest records from 1958 to 1978 aggregated species and regions. The regional harvests were disaggregated using NSW business rules assuming an historical split of 29% for region 1, 47% for region 2 and 24% for region 3. The proportion of the total prawn catch in NSW that was attributed to EKP was assumed to change over time, as the fishery developed. We assumed a 1% annual increase starting from 21% of the catch in 1958 through to 48% in 1978. All NSW regional EKP harvests were identifiable from 1979.

Qld EKP landings from 1958 to 1988 were estimated. Harvests from 1958 to 1980 were calculated from annual prawn fish-board records. For these years a number of decision rules were applied in the calculation of harvests, including a) catch was spatially limited to areas adjacent to and south of Bundaberg Port (~25°S), b) Moreton Bay harvests ≈ 38% were excluded, and c) EKP comprised a fixed proportion of 80% of the total prawn catch. Qld EKP harvests from 1989 to 2010 were tallied from compulsory commercial logbooks. Missing records on total annual EKP harvest between 1981 and 1988 (i.e., there was no dedicated logbook program at this time) were predicted from log-linear regression using 1958 to 1980 and 1989 to 2010 annual estimates ($R^2 = 0.86$). Qld EKP landings from 1958 to 1988 were expanded regionally and monthly based on generalised linear modelling (GLM) of harvest patterns using 1989 to 1994 data (Figure 17-22). Normal random uncertainty error of 0.26 (standard deviation implied from GLM analysis) was propagated monthly through 1958 to 1988.

Standardised commercial catch rates

Three catch rate analyses were conducted on New South Wales and Queensland logbook data (Table 17-1). Analyses 1 and 2 were for Qld and analysis 3 for NSW. Analyses 1 and 3 were based on whole-fleet compulsory catch reports. Analysis 2 used Qld pre-1989 EKP catch rate data from voluntary logbook databases (O'Neill *et al.* 2005; O'Neill and Leigh 2006). The regional and yearly spread of voluntary reported EKP catch was varied (Supplementary Material 1: Model data17.6.2, Figure 17-21). Data from region 6 and region 5 between 1980 and 1988 were not used due to the low number of fishing records and their high variability. Standardised monthly catch rates were estimated from the remaining voluntary data where 30 or more fishing days were recorded per month. For catch rate analysis 3, NSW business rules were used to define target EKP fishing (regions 1 to 3). EKP target fishing represented vessel-monthly records where the EKP harvest was the primary species landed (Supplementary Material 1: Model data 17.6.4).

The statistical analyses were used to standardise catch rates (Table 17-1). The analyses were linear mixed models (REML) and assumed normally distributed errors on the log scale (GenStat 2011). The linear mixed models included both fixed ($\mathbf{X\beta}$) and random ($\mathbf{Z\gamma}$) model terms, and followed the methods and terminology by O'Neill and Leigh (2007) and Braccini *et al.* (2012a). Where data $\left(\mathbf{X_1}, \mathbf{X}_2, \mathbf{X}_3, \mathbf{X}_4, \mathbf{X}_5, \mathbf{Z_1}, \mathbf{Z_2}\right)$ were relevant and available, the models were fit to estimate the following parameter effects:

- scalar model intercept β_0,
- abundance $\boldsymbol{\beta}_1$ (fishing year x month x region 3-way interaction),
- vessel gears $\boldsymbol{\beta}_2$ (log engine rated power, propeller nozzle, GPS, net type, log net length x region interaction, log mesh size, ground gear type, otter board type, BRDs and TEDs, and use of try-gear net.
- lunar phase $\boldsymbol{\beta}_3$ (for luminance and luminance shifted ¼ phase),

- fishing effort $\boldsymbol{\beta}_4$ (log hours for Qld EKP daily catches or log days for NSW EKP month catches),
- by-catch $\boldsymbol{\beta}_5$ (log NSW school whiting kgs + 0.001),
- vessels $\boldsymbol{\gamma}_1$, and
- fishing logbook grids $\boldsymbol{\gamma}_2$

Table 17-1. Linear mixed models (REML) used to standardise catch rates.

Analysis 1	**QLD: regions 4 to 6 and years 1989 to 2010.**
Response:	$\log\left(\text{kgs day}^{-1}\right)$
Fixed terms:	$\beta_0 + \mathbf{X}_1\boldsymbol{\beta}_1 + \mathbf{X}_2\boldsymbol{\beta}_2 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\beta_4$
Random terms:	$\mathbf{Z}_1\boldsymbol{\gamma}_1 + \mathbf{Z}_2\boldsymbol{\gamma}_2$
Offset:	—
Predictions:	$\boldsymbol{\beta}_1$
Analysis 2	**QLD: regions 4 to 6 and years 1969 to 1988.**
Response:	$\log\left(\text{kgs day}^{-1}\right)$
Fixed terms:	$\beta_0 + \mathbf{X}_1\boldsymbol{\beta}_1 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\beta_4$
Random terms:	$\mathbf{Z}_1\boldsymbol{\gamma}_1 + \mathbf{Z}_2\boldsymbol{\gamma}_2$
Offset:	Linearly hind-cast of deep and shallow water EKP log fishing power from $\boldsymbol{\beta}_2$ in analysis 1.
Predictions:	$\boldsymbol{\beta}_1$
Analysis 3	**NSW: regions 1 to 3 and years 1984 to 2010.**
Response:	$\log\left(\text{kgs month}^{-1}\right)$
Fixed terms:	$\beta_0 + \mathbf{X}_1\boldsymbol{\beta}_1 + \mathbf{X}_4\beta_4 + \mathbf{X}_5\beta_5$
Random terms:	$\mathbf{Z}_1\boldsymbol{\gamma}_1$
Offset:	Combined deep and shallow water EKP log fishing power from $\boldsymbol{\beta}_2$ analysis 1, and 1984 – 1988 linearly hind casted.
Predictions:	$\boldsymbol{\beta}_1$

Analysis 1 was completed with fishing power data $\mathbf{X}_2$ for $\boldsymbol{\beta}_2$. For analyses 2 and 3, the fishing power data $\mathbf{X}_2$ was not available. Therefore, the $\boldsymbol{\beta}_2$ fishing power effect was not estimated but was inserted as an offset (Table 17-1). The offset was the estimated log fishing power $\boldsymbol{\beta}_2$ for deep and shallow water EKP from analysis 1, with linear values hind casted for 1969 to 1988 (fishing power fixed terms only; Braccini *et al.* 2012a). As NSW catches were reported monthly, no lunar or grid effects could be fitted in analysis 3. Also, the corresponding NSW trawl-whiting (*Sillago robusta* and *S. flindersi*) catch effect was estimated to adjust for logbooks combining monthly effort for EKP and these alternative target species. This targeting/logbook effect was not present in Queensland waters (regions 4 to 6).

Standardised catch rates were predicted from the 3-way $\boldsymbol{\beta}_1$ interaction term, which provided abundance indices for each fishing year, month and region. No predictions were formed for missing month or region terms. The GenStat procedure "vpredict" was used to calculate monthly standardised catch rates equivalent to 2010 fleet fishing power in each region.

Standardised survey catch rates

Fishery independent surveys of EKP recruitment abundance in region 4 were conducted in the fishing years 2000 and 2007–2010. The surveys monitored EKP catch rates in the waters of Deception Bay and Moreton Bay, and the main recruitment offshore waters from the Gold Coast to Wide Bay. In the order of 200–300 beam trawl samples were conducted each year. Further details of the survey design can be found in Fisheries Queensland (2007) and Courtney *et al.* (2002; 2012).

The EKP beam trawl survey catches were analysed using a generalised linear model assuming a Poisson distribution with log link and over-dispersion (GenStat 2011; McCullagh and Nelder 1989). The response variable was based on a single trawl catch (number of EKP). The explanatory factors were sampling areas (Deception Bay, Moreton Bay, Moreton Island, Stradbroke Island and Wide Bay), months (September–December) and fishing years. Within sampling area, each trawl's swept area was constant and did not change between fishing years 2007–2010; this model term was non-significant, correlated with sampling area and therefore excluded. The focus of the analysis was to estimate the change in mean standardised catch between fishing years for use as a recruitment index. EKP mean catches were predicted by fishing year, and standardised to sampling area "Moreton Island" and month "December".

Size structured data

Two size-structured data types were used to calibrate EKP lengths within the length-spatial operating model: 1) carapace length frequencies and 2) commercial size grade frequencies, listed in Table 17-2. Together the frequencies calibrated regional and monthly changes in EKP size, to realise prawn length- selectivity and economics.

The EKP carapace length frequencies were recorded onboard commercial fishing vessels. Each prawn was sexed and measured to 1 mm length classes. From NSW, summaries of monthly length frequencies were provided for a continuous 24 month period (1991-1992, regions 1 to 3). Monthly length frequencies from Queensland waters were sporadic through time (regions 4 to 6, Table 17-2).

Table 17-2. Description of EKP size-structured data.

EKP size data	Region	Fishing years and months
Carapace lengths (mm)	1, 2 and 3	1991—1992, all 24 months
	4	1990, November and December
	4	2001, October
	5	1993, June and July
	5	2002, July
	6	2009, January
Grading categories (1 to 7)	6	September 1997 to December 2008

Five vessels operating in Queensland waters provided at-sea EKP size grading data. The grading data were recorded between 1997 and 2008 from the northern deep-waters, region 6, of the fishery. The grading categories classified prawn sizes (number of prawns per pound; heads-on and sexes combined) which were sorted into 5 kg boxes. In total 136 monthly prawn-size-box frequencies were tallied from 329612 boxes and 10947 boat-days of fishing. Seven EKP size categories were classified in the data (Table 15-6). The commercial categories (number of prawns per pound) and corresponding carapace-length classes were respectively: 1) > 30 lb^{-1} ≈ 1—27 mm, 2) 21-30 per pound ≈ 28—33 mm, 3) 16-20 per pound ≈ 34—37 mm, 4) 10-15 per pound ≈ 38—43 mm, 5) 8-10 per pound ≈ 44—47 mm, 6) 6-8 per pound ≈ 48—53 mm and 7) <6 per pound ≈ 54—75 mm. Soft and broken prawns were classified as an additional category, were of minor frequency and not analysed. No data were available to assess the accuracy of the at-sea commercial EKP size grading. However, similar small prawn boxes (3 kg) were validated as a reasonable measure for tiger prawn lengths in the Northern Prawn Fishery; particularly for the large and more valuable prawns (O'Neill *et al.* 1999).

17.3.2 Length-spatial structured model

The EKP population dynamics tracked monthly numbers (*N*) and biomass (*B*) of prawns by their sex (*s*), length (l) and spatial region (*r*) (Table 17-3). Every month (*t*) the biological processes of regional mortality, growth, movement and recruitment were taken into account. The model was run in two phases: (i) historical estimation of the EKP stock from 1958 to 2010 and (ii) simulations of EKP parameter values and uncertainty to evaluate reference points and management procedures.

In order to realise the operating model, parameters were estimated to calibrate the model to regional standardised catch rates and size-composition data (Table 17-4). Primary importance was placed on fitting the abundance (standardised catch rates from analyses 1, 2 and 3) data well (Francis 2011). Effective sample sizes were estimated for scaling multinomial likelihoods in order to calibrate to the size composition data. Due to the relatively uninformative (flat) annual trend in EKP catch rates from NSW (regions 1 to 3), a penalty function was included to prevent unrealistically large population estimates and low harvest rate estimates. Prior fitting information was given for estimating uncertainty in stock recruitment steepness (*h*), natural mortality (*M*) and annual recruitment variation (η) (Table 17-5). The calibration process compared both maximum likelihood estimation and Markov Chain Monte Carlo sampling (MCMC). The MCMC used a multivariate vector-jumping Metropolis-Hastings algorithm (Gelman *et al.* 2004). The MCMC started at the maximum likelihood parameters, with one hundred and ten thousand samples run to estimate the parameter covariance matrix and customise the vector jumping to ensure optimal acceptance ratios of about 0.2 (Gelman *et al.* 2004). A further two million samples were run with fixed covariance. To minimise autocorrelations, parameter estimates were based on one thousand posterior samples thinned from the last two million simulations. The R-coda programming package was used to analyse and confirm valid diagnostics for MCMC (R Development Core Team 2012). Goodness-of-fit plots were examined to evaluate model fits (Supplementary Material 2: Length-spatial structured model 17.7.1). The maximum likelihood parameter estimates and their covariance matrix (from MCMC) were stored for estimating reference points and running simulations.

Table 17-3. Equations for simulating EKP length and spatial population dynamics (for notation, Table 17-6.).

Monthly population dynamics	**Equations**
Number of prawns:	
$N_{l,r,t,s} = \exp(-M)\sum_{r'} \mathrm{T}_{r,r',t-1} \sum_{l'} \Xi_{l,l',r',t-1,s}\left(1 - v_{l',r'}u_{r',t-1}\right) N_{l',r',t-1,s} + 0.5R_{l,r,t}$	(1)
Recruitment number:	
$R_{l,r,t} = \dfrac{E_{y-1}}{\alpha_r + \beta_r E_{y-1}} \exp(\eta_y) \phi_{r,t} \Lambda_l$, where y indicated the fishing year.	(2)
Spawning index — annual number of eggs:	
$E_y = \sum_t \sum_r \sum_l N_{l,r,t,s} m_{l,r} f_l \theta_r$	(3)
Recruitment pattern — normalised monthly proportion:	
$\phi_{r,t} = \exp\left[\kappa \cos\left\{2\pi(t-\mu)/12\right\}\right] \Big/ \sum_{t'=1}^{12} \exp\left[\kappa \cos\left\{2\pi(t'-\mu)/12\right\}\right]$,	(4)
where t indicated time-of-year months 1…12.	
Mid-month exploitable biomasses—forms 1 and 2:	
$B^1_{r,t} = \sum_l \sum_s N_{l,r,t,s} w_{l,s} v_{l,r} \exp(-M/2)$ $B^2_{r,t} = \sum_l \sum_s N_{l,r,t,s} w_{l,s} v_{l,r} \exp(-M/2)\left(1 - u_{r,t}/2\right)$	(5)
Harvest rate:	
$u_{r,t} = C_{r,t} \big/ B^1_{r,t}$, where C was a regions monthly harvest kgs.	(6)
Prawn vulnerability to fishing:	
$v_{l,r} = \dfrac{1}{1 + \exp\left(\delta\left(l^{50}_r - l\right)\right)}$	(7)
Fishery data indicators—catch rates:	
Fishery (f; kg boat-day^{-1}): $c^{\mathrm{f}}_{r,t} = q^{\mathrm{f}}_{r,t^m} B_{r,t} \exp\left(\varepsilon^{\mathrm{f}}_{r,t}\right)$, where t^m indicated average monthly values 1…12 for each region r. Survey (s; number trawl-shot^{-1}): $c^{\mathrm{s}}_{r=4,y} = q^{\mathrm{s}}_4 \bar{R}_{4,y(1,2)} \exp(-M/2) \exp\left(\varepsilon^{\mathrm{s}}_{4,y}\right)$ for r=4, fishing months = Oct(1) and Nov(2)	(8)

Table 17-4. Negative log-likelihood functions for calibrating population dynamics.

-LL **functions for:**	**Theory description**	**Equations**
Log standardised catch rates (c^{f} or c^{s} **):** $\frac{n}{2}\left(\log(2\pi)+2\log(\hat{\sigma})+1\right)$, 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 catch rate data.	Normal distribution (Haddon 2001)	(9)
Length (l **) and box-grading (** g **) size-composition data:** $-\sum\left(\log\left(\nu^{(\tilde{n}-1)/2}\right)-\left(\frac{1}{2}(\tilde{n}-1)\frac{\nu}{\hat{\nu}}\right)\right)$, or simplified as $-\sum\frac{1}{2}(\tilde{n}-1)\left(\log\nu-\nu/\hat{\nu}\right)$, where $\tilde{n}$ was the total number of size categories (l or g) with proportion-frequency > 0, $\hat{\nu}=(\tilde{n}-1)/2\sum\hat{p}\log(\hat{p}/p)$, $\nu=\max(2,\hat{\nu})$ specified sample size bounds, $\hat{p}$ were the observed proportions > 0 and p were predicted.	Effective sample size (ν) in multinomial likelihoods (Leigh 2011; O'Neill *et al.* 2011)	(10)
Preventing unrealistically large population estimates and low estimates of harvest rate: $0.5\left(\frac{\tilde{u}-\max\left(CN_y/R_y\right)}{\sigma}\right)^2 b$, where $\tilde{u}$ was the minimum annual harvest fraction 0.2, σ was the user defined std for penalty weighting (0.005), CN_y was the annual total number of EKP caught over the regions, R_y the annual recruitment, and b was a logical switch for $\max\left(CN_y/R_y\right)<\tilde{u}$. The penalty was applied between 1992 and 2010.	Optimisation penalty (Hall and Watson 2000)	(11)

Table 17-5. Negative log-likelihood functions for parameter bounds and distributions.

-*LL* functions for:	Equation
Stock recruitment steepness h**:**	
$0.5\left(\frac{\text{logit}(h)-\text{logit}(0.5)}{\sigma}\right)^2$, where $\sigma = 0.7$ defined a broad prior distribution.	(12)
Instantaneous natural mortality M month^{-1}**:**	
$0.5\left(\frac{M-0.18}{\sigma}\right)^2$, where $\sigma = 0.05$ defined the prior distribution $\cong$ 28% CV.	(13)
Annual log recruitment deviates η_y**:**	
$\frac{n}{2}\left(\log(2\pi)+2\log(\sigma)+(\hat{\sigma}/\sigma)^2\right)$, or simplified as $n\left(\log\sigma+\frac{1}{2}(\hat{\sigma}/\sigma)^2\right)$, where $\sigma=\min\left(\max(\hat{\sigma},\sigma_{\min}),\sigma_{\max}\right)$, $\sigma_{\min}=0.1$ and $\sigma_{\max}=0.4$ specified bounds, $\hat{\sigma}=\sqrt{\sum\eta_y{}^2/n}$ and n was the number of recruitment years y.	(14)

Table 17-6. Length – spatial population model parameters, values and definitions.

Model parameters	Equations, values and errors	Notes
Assumed		The values and errors were calculated from published research or data.
T	$p_{4\to6} = p_{4\to5}\dfrac{\exp(\rho)}{1+\exp(\rho)}$, where ρ was an estimated logit variable.	Transition probability matrix (6x6) for moving EKP between regions $r' \to r$. The matrix was calculated by aggregating finer scale probabilities to produce an approximate Markov process at the larger region scale (Braccini *et al.* 2012b). Tag-recapture data was too limited to quantify northern EKP transitions from region 4 to 6. This probability was estimated to be proportional to the region 4 to 5 transition. Twelve matrices were used to vary movement by time-month *t* (Figure 17-38).
Ξ	$\text{lat} = [-32.0, -29.5, -28.5, -26.5, -26.5, -23]$ $\sigma_{\text{male}} = 2.069; \sigma_{\text{female}} = 2.277$	Growth transition matrix allocated a proportion of EKP in carapace length-class l' at time *t*-1 to grow into a new length l over one time-month *t*. The transitions varied with prawn sex *s*, region *r* and month *t*, and assumed a normal probability density function (O'Neill *et al.* 2010; Punt *et al.* 2010; Sadovy *et al.* 2007). The growth model was based on the latitudinal and seasonal estimates of EKP (Lloyd-Jones *et al.* 2012); Figure 17-41. Their *k* and θ_1 parameters were rescaled per degree and month, "lat" specified the degree latitude for each region and σ were the standard deviations of the monthly growth increment, in mm.
Λ	Summary percentiles [2.5 25 50 75 97.5] = 13, 18, 22, 27 and 35 mm.	Proportion of EKP recruitment in length class l (1…75 mm). The proportions were calculated from a lognormal distribution for length at recruitment, based on region 4 monitoring data in fishing years 2000 and 2007 to 2010 (Figure 17-39). The frequencies were approximately equal for male and female EKP (Courtney *et al.* 2002).
w	$w_{l,s} = a_s l^{b_s} / 1000$, $a_{\text{male}} = 0.0017, b_{\text{male}} = 2.7005$, $a_{\text{female}} = 0.0021, b_{\text{female}} = 2.6333$	Average EKP weight (kg) at length l for sex *s* (Courtney 1997).
f	$f_l = 10^{(al+b)}$ $a = 0.0199; b = 4.7528$	Fecundity (egg production) at length per female EKP (Courtney 1997; Montgomery *et al.* 2007); (Figure 17-40).
m	Summary of maturity schedule: $l_{50} = 38; l_{95} = 45$ for $r = 3,5,6$ $l_{50} = 40; l_{95} = 45$ for $r = 1,2,4$	Logistic maturity schedule by carapace length (mm) and region (Figure 17-40). The schedule was estimated using binomial regression and logit link, m ~ Constant + Year + Month + Region/Length; adjusted $R^2 = 0.746$. The GenStat model terms Year, Month and Region were factors, while Length was a variate.
θ	θ =[0.15, 0.33, 0.6, 0.6, 0.6, 0.75]	Proportion of EKP spawning by region (Montgomery *et al.* 2007); (Figure 17-40).

Table 17-6. . Continued.

Model parameters	Equations, values and errors	Notes
Estimated	N=69	The values and their variances and covariance's were estimated.
ξ and Υ_r	$\alpha_r = E_0(1-h)/(4hR_{0,r})$ $\beta_r = (5h-1)/(4hR_{0,r})$ $R_{0,r} = \exp(\Upsilon_r)\times 10^8$ $h = \exp(\xi)/1+\exp(\xi)$	Five parameters for the Beverton-Holt spawner-recruitment equation 2 (Table 17-3), that defined α and β (Haddon 2001). Virgin recruitment (R_0) was estimated on the log scale separately for regions 1 to 4 in 1958. One estimated logit value of steepness (h) was assumed for the EKP stock, with prior distribution equation 12 Table 17-5. E_0 was the calculated overall virgin egg production for the EKP stock.
μ and κ	μ_r for each region 1 to 4. κ_1 for regions 1 to 3 (New South Wales). κ_2 for region 4 (Queensland).	Six parameters for the estimated mode (μ) and concentration (κ) of the monthly (time-months 1…12) recruitment patterns, equation 4 (Table 17-3); according to a von Mises directional distribution (Mardia and Jupp 2000).
l^{50} and δ	l_1^{50} for region 1. l_2^{50} for regions 2 to 4. l_3^{50} for regions 5 and 6.	Four parameters for the estimated logistic vulnerability, equation 7 (Table 17-3). δ governed the initial steepness of the curve and l^{50} was the length at 50% selection by region
M	Normal prior distribution	One parameter for instantaneous natural mortality month^{-1}, with prior distribution equation 13 Table 17-5. The prior distribution allowed for two to three years longevity (Lloyd-Jones *et al.* 2012), and values around those used in previous EKP modelling (Lucas 1974; O'Neill *et al.* 2005). Ives and Scandol (2007) summarised estimates of EKP M ranging from 0.13 to 0.35, with values ≥ 0.24 possibly biased upwards (Glaister *et al.* 1990).
ρ	See variable T	One parameter was estimated for calculating EKP movement from region 4 to 6.

ζ	$\boldsymbol{\eta} = \boldsymbol{\zeta}\mathbf{e}$
	 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 recruitment deviations sum (and mean) to zero with standard deviation σ, equation 14 Table 17-5. ζ were the estimated parameters (Figure 17-27) known as barycentric or simplex coordinates, distributed $NID(0,\sigma)$ with number nparRresid = number of recruitment years – 1 (Möbius 1827; Sklyarenko 2011). $\mathbf{e}$ was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill *et al.* 2011).

q^{f}_{r,t^m} and q^{s}_4		Closed form estimates of EKP catchability (Haddon 2001). Each region's catchability was calculated as monthly means of standardised catch rates divided by the mid-month biomass (form 2). Each regions monthly pattern of catchability was the same in each year. Survey catchability was a single mean value of standardised survey catch rates divided by region 4 recruitment adjusted by $\exp(-M/2)$.

17.3.3 Delay difference model

The Deriso-Schnute delay difference model was used in this study to assess the eastern king prawn stock as a single-entity across Queensland and New South Wales waters (Quinn and Deriso 1999; Schnute 1985). The model simplified the population mathematics and provided a comparison against the more complex length-spatial model. The model also allowed for easier testing of key data uncertainties. Historically, the Deriso-Schnute delay difference model was used to assess eastern king prawns in 2001 and 2004 (Ives and Scandol 2007; O'Neill *et al.* 2005). The model also assessed Torres Strait tiger prawns (O'Neill and Turnbull 2006) and Northern Australia's tiger prawns (Dichmont *et al.* 2001). These past assessments were all independently reviewed and positively accepted.

The dynamics of the delay difference model operated on monthly time steps t:

$$B_t = (1+\rho)B_{t-1}s_{t-1} - \rho s_{t-1}s_{t-2}B_{t-2} - \rho s_{t-1}w_{r-1}R_{t-1} + w_r R_t$$

where B was the exploitable biomass of eastern king prawns (kg), ρ was the growth parameter (Table 17-7; estimated outside the delay difference model following Schnute (1985) and illustrated in Figure 17-3), s was prawn survival $\exp(-M)(1-\text{Catch}/B)$, w was the mean weight kg of recruiting prawns (Table 17-7) and R was the number of newly recruited prawns. Recruitment R was assumed to follow an annual Beverton and Holt function with lognormal deviations multiplied by a monthly recruitment probability calculated from a normalised von Mises directional distribution (Table 17-3). The approximate number of female EKP spawning each year y was:

$$S_y = 0.5\sum_{t=1}^{12}\theta\frac{1-\exp(-Z_t)}{Z}N_t,$$

where Z_t was the monthly total mortality and N_t the exploitable population number of EKP. The methods were further described in O'Neill *et al.* (2005) and O'Neill and Turnbull (2006).

Both whole-of-fishery (described in Supplementary Material 3: Delay difference model 17.8.1) and region-4-survey standardised time series of catch rates were tuned as abundance indices assuming a lognormal distribution. Predicted fishery catch rates were adjusted to mid-month values. Predicted survey catch rates were fitted against annual recruitments. Closed form of their catchability coefficients were calculated as an average (Haddon 2001). Four different model fits were considered (Table 17-8 and Table 17-9) examining assumptions for natural mortality, historical harvest and fishing power. Five negative log-likelihoods (Table 17-4 and Table 17-5) were summed with equal weight into a single objective function: 1. commercial catch rates, 2. region-4 survey catch rates, 3. stock recruitment steepness h, 4. natural mortality, and 5. recruitment deviates; these were described in section 17.3.2. Bias corrected confidence intervals on model outputs were generated from bootstrapping (Haddon 2001).

The main assumptions of the delay difference model were:

- catch rates were proportional to abundance,
- constant natural mortality and catchability,

- mean growth function for prawn weight over both sexes combined,
- age at first recruitment to the fishery and age at maturity were both equal to 4 months, and
- all prawns of all sizes were equally and fully vulnerable.

Table 17-7. Eastern king prawn biological parameters for the delay difference model.

Parameter	Estimates
Von Bertalanffy prawn growth (Lloyd-Jones et al. 2012)	
Female L_∞	57.4 $\pm$ 2.98 mm CL
Male L_∞	44.9 $\pm$ 1.62 mm CL
Female k	2.03 $\pm$ 0.266 per year
Male k	2.45 $\pm$ 0.300 per year
Carapace length (mm) to weight (grams) (Courtney 1997)	
Female *a*	0.00168
Male a	0.00102
Female b	2.7
Male b	2.839
Ford model for sexes combined prawn growth (Hilborn and Walters 1992; Schnute 1985)	
ρ	0.875; estimated.
w_r	11.7 g ; fixed recruitment weight at age 4 months
w_{r-1}	3.00; estimated pre-recruitment weight.
Proportion of EKP spawning (Table 17-6.)	
θ	0.6

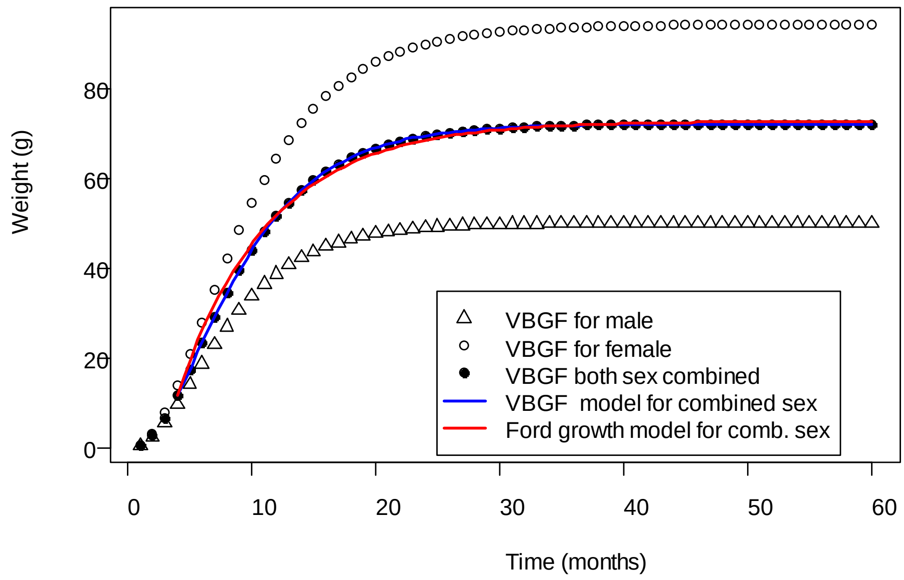


Figure 17-3. Comparison between Von Bertalanffy growth function (VBGF) and Ford model description of the mean weight at age of eastern king prawns.

Table 17-8. Description of the delay difference models.

Model No.	Description	Number of estimated parameters.
Model 1	S/R relationship (2 pars); 52 S/R deviates; von Mises recruitment distribution over 12 months (2 pars); fixed M at 0.18 month^{-1}	56
Model 2	As above but M was estimated	57

Table 17-9. Summary of sensitivity tests conducted on model 1.

Sensitivity 1	Larger historic total harvest pre compulsory logbooks (<1984 NSW, <1989 QLD): best estimate * 1.3.
Sensitivity 2	Qld catch rates pre 1988 standardised using a 20% lower fishing power change, rather than best estimate (Figure 17-52).

17.3.4 Economic model and parameters

The economic model calculated net present value (NPV) following the methods for assessing Australia's Northern Prawn Fishery (Punt *et al.* 2010). The NPV objective function summed profits over model future-projections:

$$\text{NPV} = \sum_{y=1}^{T-1} \frac{\pi_y}{(1+i)^{y-1}} + \frac{[\pi_T / i]}{(1+i)^{T-1}},$$

where i was the annual interest (discount) rate, π_y the profit during year y, and π_T the profit in terminal year T (last year of the future projection). For this function, the fishery was assumed to be in equilibrium in the terminal year and hence the level of profit in this year would continue indefinitely.

Annual profit was calculated as catch value minus variable and fixed cost components:

$$\pi_y = \sum_r \left(\sum_t \left(\sum_l v_{r,t,l} C_{r,t,l} - \Omega^{\text{V}}_{r,t} \right) + \bar{B}^{by}_r E_{r,y} - \left(\Omega^{\text{F}}_{r,y} \frac{E_{r,y}}{\bar{d}_r} \rho \right) \right),$$

where $v_{r,l,t}$ was the average EKP prawn price in region r, time-month t and length class l (Figure 17-4), $C_{r,t,l}$ was the EKP harvest tonnage, $\Omega^{\text{V}}_{r,t}$ was the total variable costs, $\bar{B}^{by}_r$ was the average by-product value ($) taken each boat-day, $E_{r,y}$ was the total annual boat-days fished, Ω^{F}_y the average annual fixed costs, $\bar{d}$ was the mean number of days fished per boat year and ρ was the fraction of fixed costs allocated to the EKP fishery (Table 17-10). The division by $\bar{d}_r$ allowed the annual number of vessels to change based on profitability.

Variable costs $\Omega^{\text{V}}_{r,t}$ were calculated by region r and time-month t. This included the proportional share for fishing labour (c_L), proportional cost of packaging and marketing (c_M), repairs and maintenance cost per boat-day (c_K), fuel cost per boat-day (c_F), and other incidental costs per boat-day (c_O) (Table 17-10):

$$\Omega^{\text{V}}_{r,t} = \sum_l \left(c_{L_r} v_{r,t,l} + c_{M_r} \right) C_{r,t,l} + \left(c_{K_r} + c_{F_r} + c_{O_r} \right) E_{r,t}.$$

Average annual fixed costs $\Omega^{F}_{r,y}$ were calculated using regional vessel costs (W_r), and opportunity (o) and deprecation (d) rates on average total investment value per vessel ($K_{r,y}$) (Table 17-10):

$$\Omega^{F}_{r,y} = \left(W_r + (o+d)K_{r,y}\right).$$

Annual vessel costs (W_r) were not related to fishing effort. They were the sum of costs needed to support a vessel before fishing. Collectively, insurance and licence/industry fees accounted for 50% of annual vessel costs (W_r), and the primary hull plus electronics represented 88% of total investment ($K_{r,y}$); see 17.9. Supplementary Material 4: Economic data

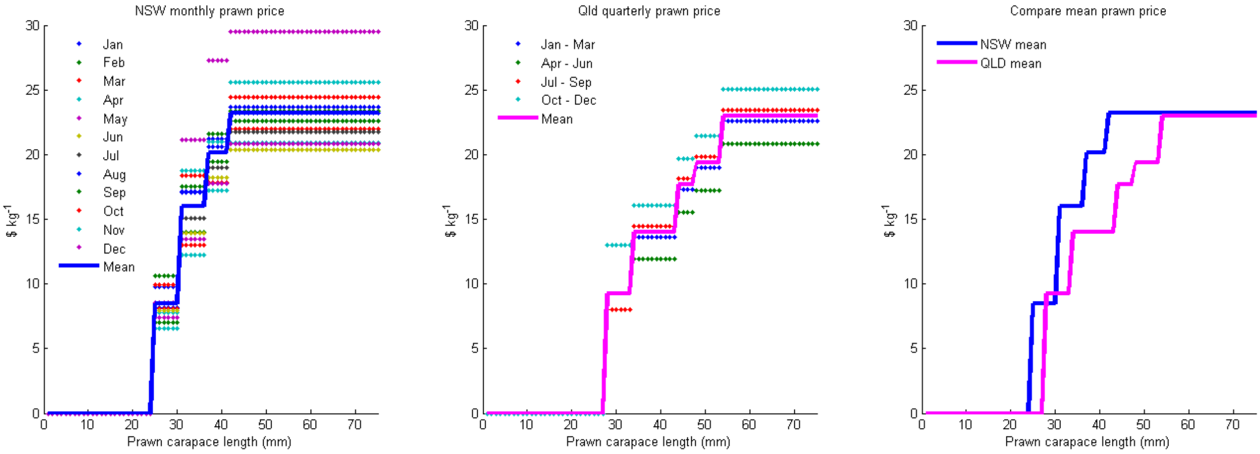


Figure 17-4. Average 2010 eastern king prawn landing-prices (\$ kg^{-1}) by pawn size and capture time for New South Wales and Queensland. The data were from the NSW Sydney fish market and a Queensland processor representative.

Queensland fuel cost (c_F) averages and variances were calculated using 2010 regional fuel use and average fuel price of \$0.85 litre^{-1} (Figure 17-5). The fuel use data were sourced from the Queensland catch-rate standardisation files covering in order of 200 different vessels. Fuel costs (cF) for New South Wales were based on Queensland inshore vessels (region 4), adjusted down for smaller vessel average standardised hull units (35 compared to 50 in Queensland; 17.9 Supplementary Material 4: Economic data, Table 17-21). New South Wales vessel repairs (c_K), annual vessel costs (W_y) and total investments (K_y) were also adjusted for lower SHU (Table 17-21). Standardised hull units (*SHU*), a management unit defining a vessel's average fishing power (O'Neill and Leigh 2006; QECTMP 2001), were calculated by the equation $SHU = 2.4052 \times HU^{0.7617}$. Hull units (*HU*) defined the under deck volume of a vessel: $HU = \left(length \times beam \times depth \times 0.6\right)/2.83$.

The variable (other than fuel) and fixed cost parameters (means and variances) were based on questionnaire responses from 24 vessel owners from the Queensland fishery (detailed in 16.3.3 and 16.3.4). The survey coverage of the 2010 fleet was low. However, the average fishing capacity of the economic sample of vessels was representative compared to the 2010 fleet respectively (vessel length 17m vs. 17.5m;

SHU 48 vs. 50; hours fished per boat-day 10.7hrs vs. 10.4hrs). The final parameter values were reviewed and accepted by steering committee members.

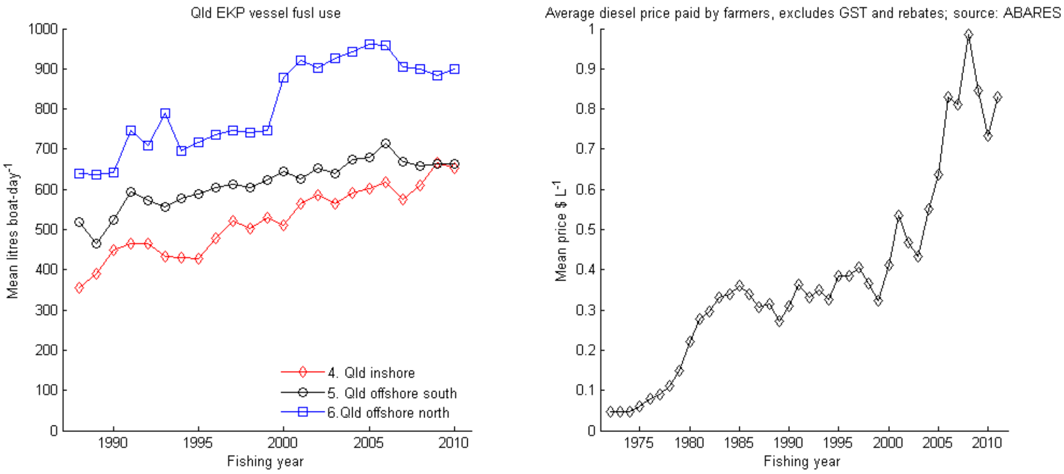


Figure 17-5. Average fuel use by vessels fishing in Queensland waters and average net fuel price paid (ABARES 2011).

Table 17-10. Input parameter values and their 95% confidence intervals for the economic model.

Parameters		New South Wales		Queensland	States combined (weighted mean)
Variable costs:					
Labour (*cL*: proportion of catch $)		0.29 (0.2 : 0.39)		0.29 (0.2 : 0.39)	0.29
Packaging (*cM*: $ kg^{-1})		0.41 (0.28 : 0.54)		0.41 (0.28 : 0.54)	0.41
Repairs (*cK*: $ $boat\text{-}day^{-1}$)		288.63 (201.26 : 415.74)		407.46 (320.82 : 520.1)	384
Fuel (*cF*: $ $boat\text{-}day^{-1}$)	Reg. 1	526.79 (476.8 : 576.37)	Reg. 4	546.35 (494.58 : 597.76)	619
Fuel (*cF*: $ $boat\text{-}day^{-1}$)	Reg. 2	526.4 (476.99 : 575.11)	Reg. 5	563.1 (512.04 : 615.42)	
Fuel (*cF*: $ $boat\text{-}day^{-1}$)	Reg. 3	526.11 (477 : 576.45)	Reg. 6	760.19 (708.98 : 812.81)	
Incidentals (*cO*: $ $boat\text{-}day^{-1}$)		44.26 (22.98 : 65.98)		44.26 (22.98 : 65.98)	44.26
Annual fixed costs:					
Vessel costs (*Wy*: $ $boat^{-1}$)		28637 (23608 : 34769)		46170 (39403 : 53998)	42646
Total investment (*Ky*: $ $boat^{-1}$)		255330 (191910 : 338710)		673590 (551810 : 817980)	589719
Proportion allocated to EKP (ρ)		0.5 (0.4 : 0.6)		0.67 (0.57 : 0.76)	0.63
Revenue from by-product:					
Catch value (*by*: $ $boat\text{-}day^{-1}$)	Reg. 1	195.91 (182.15 : 209.65)	Reg. 4	221.89 (86.7 : 349.14)	143
	Reg. 2	211.42 (177.06 : 244.26)	Reg. 5	122.26 (52.08 : 192.01)	
	Reg. 3	112.87 (100.99 : 124.95)	Reg. 6	62.91 (2.73 : 122.84)	
Annual fishing effort:					
Mean number of days $boat\text{-}year^{-1}$		42 (33 : 52)		74 (66 : 83)	68
Annual economic rates:					
Interest rate (i)		0.05 (0.034 : 0.072)		0.05 (0.034 : 0.072)	0.05
Opportunity cost (o) = i					
Depreciation rate (d)*		0.02 (0.02 : 0.037)		0.02 (0.02 : 0.037)	0.02

* Uniform variation between lower and upper confidence intervals.

17.3.5 Reference points and management procedures

Model simulations were used to estimate management reference points and evaluate the proposed management procedures. The simulations were driven by forward projection methodology similar to Richards *et al.* (1998). For driving the simulations, one thousand multivariate length-spatial parameter estimates were created from the MCMC covariance matrix. Bootstrap parameter estimates were used for the delay difference model. For economics, one thousand random variations on Table 17-10 were generated based on each variable's variance. The parameters were used to simulate future realities. The projections were conducted under two conditions: 1) deterministic recruitment to estimate equilibrium maximum sustainable yields (MSY: objective to maximise annual harvest) and maximum economic yields (MEY: objective to maximise Net Present Value for fishing vessels) and 2) stochastic recruitment to evaluate management procedures over 2011 to 2020 in the length-spatial model only.

The calculation of reference points for MSY and MEY were based on optimising the population and economic models through mean monthly fishing mortality ($\propto$ fishing effort; note all parameter uncertainties were included except stochastic recruitment variation). The EKP population dynamics were propagated into equilibrium according to Beverton-Holt spawner-recruitment function, monthly fishing pattern and mortality. The following monthly patterns of fishing mortality and variance were considered: a) status quo = pattern over the last five years 2006 to 2010 (17.10 Supplementary Material 5: Model projection data, Figure 17-56), b) historical 1995 to 1999 pattern adjusted for a Jan closure (17.10 Supplementary Material 5: Model projection data, Figure 17-57), and c) an optimised average fishing pattern for each region. In total ten MSY and MEY optimisations were conducted (five combinations of effort patterns by two economic conditions; Table 17-11). Only the status quo pattern was used to estimate MSY and MEY in the delay difference model.

A constrained optimisation was used to assess if MSY or MEY could be increased by changing the monthly effort pattern in each region. For the length-spatial model optimisations 5 and 10 (Table 17-11), the von Mises function was used (described in equation 4 Table 17-3 and Table 17-6; but normalised with mean = 1) with six regional modes (μ_r) and two State concentration ($\kappa_{\text{NSW,QLD}}$) parameters. Constraints were used to maintain the mean monthly fishing mortality within the minimum and maximum solutions under optimisations 1 to 4 or 7 to 10 (Table 17-11). Fishing was constrained to spread throughout the year ($0.1 \le \kappa_{\text{NSW,QLD}} \le 1$) (Matlab: fmincon, MathWorks 2012).

Table 17-11. Definition of the ten MSY and MEY optimisations with the length-spatial population and economic models. The assumed fishing patterns were listed by region.

Opt. No.	Economic parameters	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
1	Constant	a) SQ	a) SQ	a) SQ	a) SQ	a) SQ	a) SQ
2	Constant	b) Jan	a) SQ	a) SQ	b) Jan	a) SQ	a) SQ
3	Constant	a) SQ	a) SQ	a) SQ	b) Jan	b) Jan	b) Jan
4	Constant	b) Jan	b) Jan	b) Jan	b) Jan	b) Jan	b) Jan
5	Constant	c) est.	c) est.	c) est.	c) est.	c) est.	c) est.
6	Var. and FP ↑ 3% p.a.	a) SQ	a) SQ	a) SQ	a) SQ	a) SQ	a) SQ
7	Var. and FP ↑ 3% p.a.	b) Jan	a) SQ	a) SQ	b) Jan	a) SQ	a) SQ
8	Var. and FP ↑ 3% p.a.	a) SQ	a) SQ	a) SQ	b) Jan	b) Jan	b) Jan
9	Var. and FP ↑ 3% p.a.	b) Jan	b) Jan	b) Jan	b) Jan	b) Jan	b) Jan
10	Var. and FP ↑ 3% p.a.	c) est.	c) est.	c) est.	c) est.	c) est.	c) est.

Table footnotes:

a. Constant = constant 2010 economics (Table 17-10) and fishing power.

b. Var. and FP ↑ 3% p.a. = economic variable costs and fishing power (FP) were increased at 3% p.a.

c. Regional effort patterns: a) status quo (SQ) = average pattern 2006 to 2010 (Supplementary Material 5: Model projection data, Figure 17-56), b) historical 1995 to 1999 pattern adjusted for a Jan closure (Supplementary Material 5: Model projection data, Figure 17-57), and c) an optimised average fishing pattern for each region.

Management procedures were developed through a series of meetings with managers, stakeholders and scientists (Table 17-12). Management scenarios considered one-monthly trawl closures, a cap on total fishing effort and within-year catch-rate control-rules. In total 18 management scenarios, projected over 10 future years, were investigated. These included assumptions pertaining to annual increases in operational costs and fishing power. The following performance measures were used: (i) industry functioning – average annual harvest and effort, (ii) economics – relative net present value (NPV) and average catch rates, and (iii) 2020 population status – spawning egg production and biomass.

Table 17-12. New South Wales and Queensland eastern king prawn management procedures simulated over ten future years in the length-spatial model. Note these were proposed for simulation modelling only and not Fisheries policy.

Management brief	**Management procedures**		
	Total effort (max boat-days)	**Regions closed**	**Month closed (month number)**
1. Status quo.	Max last five years, $\sum \approx$ 30000	Qld inshore (area 4)	Oct (12)
2. Close NSW southern and Qld inshore waters in January.	Max last five years, $\sum \approx$ 30000	NSW (area 1) Qld (area 4)	Jan (3)
3. Close Qld waters in January.	Max last five years, $\sum \approx$ 30000	Qld waters (areas 4 to 6)	Jan (3)
4. Close all NSW and Qld waters in January.	Max last five years, $\sum \approx$ 30000	All waters (areas 1 to 6)	Jan (3)
5. Limit total effort to E_{MEY}, and close all waters in January.	$E_{MEY} \approx 9000$	All waters (areas 1 to 6)	Jan (3)
6. Limit total effort to E_{MSY}, and close regional waters on catch rate thresholds.	$E_{MSY} \approx 44000$	Variable m_r to Oct (12)	
7. Limit total effort to E_{MEY} and close regional waters on catch rate thresholds.	$E_{MEY} \approx 9000$	Variable m_r to Oct (12)	

Table footnotes:

A. **Months:** Fishing year months (m) were ordered from 1=Nov to 12=Oct. The time closed Oct (12) ≈ current Qld southern shallow water closure.

B. **Regions:** Areas (*r*) were ordered from south to north, where NSW sth =1, NSW mid = 2, NSW nth = 3, QLD inshore = 4, Qld deep sth = 5, Qld deep nth =6.

C. **Closures m_r:** Calculate adaptive closures for different areas and months (Jan to Oct) based on catch rate thresholds $m_r = \text{firstmonth}\left(cr_{r,m} < cr_{r,.m}^{\text{limit}}\right) + 1$, where $cr_{r,m}$ was the standardised catch rate (kgs) for region *r* and month m, $cr_{r,.m}^{\text{limit}}$ was the standardised catch rate reference point, and +1 month provides industry time to prepare for area shut down. The first two months of the fishing year, November and December, were always open.

D. **Fishing effort:** Total effort was split across areas and months based on historical patterns (17.10 Supplementary Material 5: Model projection data). Beta distribution was assumed for implementation error on $E_{status\text{-}quo}$ and E_{MSY} fishing efforts; based on the ratio of 2006-2010 fishing effort to $E_{status\text{-}quo}$. If a region was closed from fishing, a proportion of remaining fishing effort was reallocated to other regions (17.10.2 Fishing effort movement matrix).

E. **Conditions:** The management procedures were simulated over ten future years using a) fixed 2010 fishing costs and power and b) increased fishing costs and power (@ 3% $year^{-1}$).

17.4 RESULTS

17.4.1 Model calibrations

Length-spatial model

Of primary focus were the dynamics of the EKP population spanning NSW and Qld waters. Analysis of standardised residuals indicated that the length-spatial model fitted the data appropriately and that the assumed error structures were valid (Supplementary Material 2: Length-spatial structured model, 17.7.1). No concerning correlations of key parameter estimators were evident.

The model predicted the EKP fishery standardised catch rates reasonably well, although region 2 EKP catch rates were less seasonal and less predictable. Standard deviations of log-fits were 0.34, 0.39, 0.24, 0.33, 0.18, and 0.16 for regions 1 to 6 respectively; region 4 deviations were inflated by the more variable pre-1988 voluntary logbook records. No patterns or significant autocorrelations in standardised residuals were evident. Normality plots were linear for more than 95% of the residuals. Regional standard deviations of standardised residuals were marginally less than 1 (reporting SDNR; Francis 2011).

Model fits to region 4 EKP recruitment indices were not influential due to the limited 5-year time series (σ = 0.21; SDNR = 1.11, less than $\mathrm{sqrt}\left(\chi^2_{0.95,4}/4\right) = 1.54$).

Model calibration to the length- and grading-frequency data was scaled by their effective sample size ($\approx$i.i.d. sampling of prawns). Using effective sample size ensured primary fitting to the catch rate data and helped gauge the representativeness of the length and grading data. Low effective sample sizes are typical for fisheries data and for EKP the visual lack of fit in some months indicated non-representative samples rather than poor estimation of EKP lengths. For region 6 where large prawns are caught, the model predicted the grading data reasonably well.

The length-spatial model predicted that historical EKP spawning egg production and exploitable biomass, expressed as a median ratio relative to 1958, had declined roughly 40–50% up to 1985 and remained steady to 2006 (Figure 17-6). The median ratios had increased since 2006 and were 60–80% of 1958 levels.

It should be noted that the above result depended on the validity of the standardised EKP catch rates calculated from pre-1989 voluntary logbook data; see 0 Discussion.

Based on the pre-specified regional movement probabilities, roughly 50% of fishery EKP recruitment was estimated to enter region 4 and 30% in region 2. Typical recruitment modes were estimated in February, December, October and November for regions 1 to 4 respectively. No large yearly variation in catch rates was evident and annual log recruitment standard deviation was estimated at 0.12, which is quite low. Recruitment steepness was calibrated at 0.38. EKP mean carapace length at 50% vulnerability was 21 mm in region 1, 25 mm in regions 2 to 4 and 35 mm in regions 5 and 6. Instantaneous natural mortality was calibrated to 0.19 month^{-1}. See Supplementary Material 2: Length-spatial structured model, 17.7.1 for further model diagnostics.

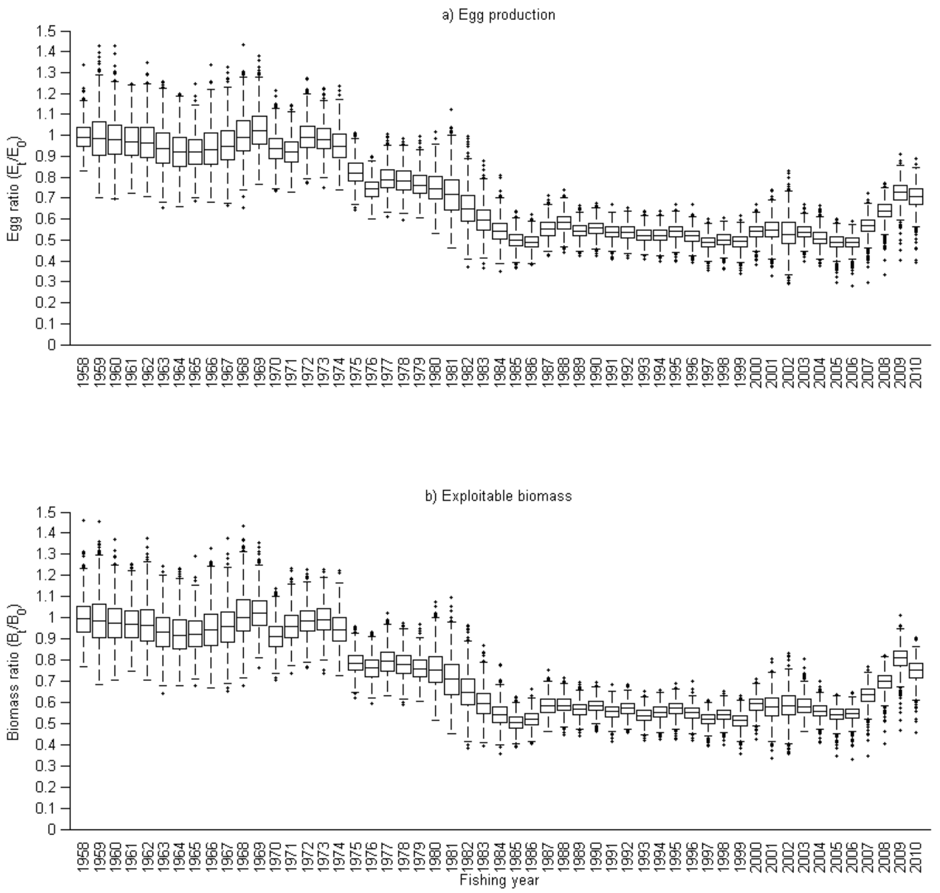


Figure 17-6. Box-plots of estimated yearly change in eastern king prawn a) egg production and b) exploitable biomass from the length-spatial model. The plots display the simulated distributions (1000 samples; expressed as a ratio of virgin eggs E_0 and biomass B_0) around their medians (line in the middle of each box). The tops and bottoms of each "box" are the 25th and 75th percentiles respectively. Ratios beyond the whisker length ($\approx 2.7\sigma$) are marked as low probability estimates.

Delay difference model

The EKP whole-stock delay difference model simplified the population dynamics and provided a comparison against the more complex length-spatial model. The model was notably different in that it was tuned to a single time-series of standardised catch rates (averaged over the regions, Supplementary Material 3: Delay difference model, 17.8.1). No penalty log-likelihood was required as the single catch rate time series contained sufficient tuning contrast. Also catchability was assumed a single value, rather than seasonal.

Overall, the delay difference model tracked the trend in standardised catch rates reasonably well (σ = 0.15, SDNR marginally < 1; Supplementary Material 3: Delay difference model, 17.8.2). Standardised residuals were normally distributed. A slight within-year pattern of standardised residuals was present where the model marginally underestimated the monthly peak catch rates and overestimated the monthly minima;

due to the constant q assumption. As for the length-spatial model, the Queensland voluntary EKP catch rates resulted in higher variance before 1988.

Four model fits were explored (Table 17-8 and Table 17-9). Models 1 and 2 predicted historical EKP exploitable biomass ratios at a low of about 40% in 1985, then varied around 50–60% to 2006, and increased to about 75% in 2010 (Figure 17-7). Sensitivity 1 estimated a declined exploitable biomass ratio at 50% in 2006 and an increase to 65% in 2010 (Figure 17-8). Large uncertainty was estimated for sensitivity 2 and produced unreliable results when assuming low fishing power (Figure 17-8). Model 2 estimated natural mortality at 0.21 month^{-1} and virgin recruitment was estimated similar to the length-spatial model. For the whole EKP stock, the modal recruitment month was December. Recruitment steepness was estimated at about 0.27 for models 1 and 2, and 0.32 for sensitivity 1. Please refer to Supplementary Material 3: Delay difference model,17.8.2 for more diagnostics.

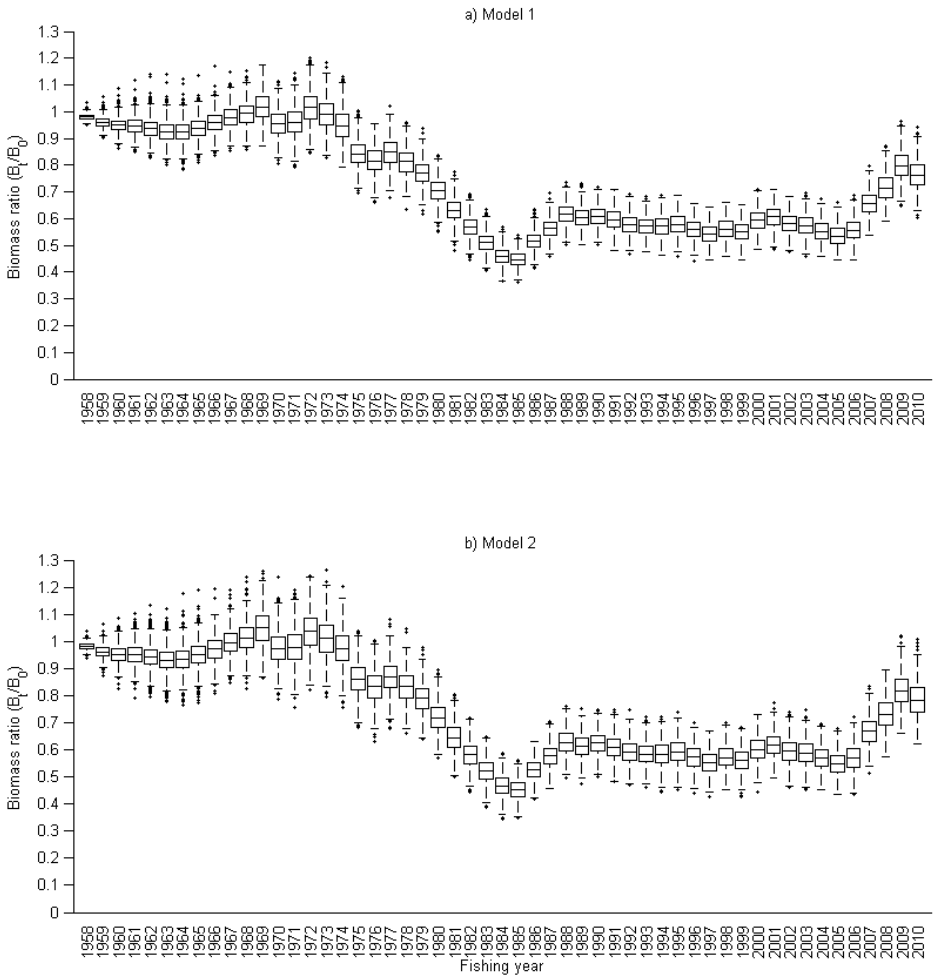


Figure 17-7. Box-plots of estimated yearly change in eastern king prawn exploitable biomass from a) delay difference model 1 with fixed M=0.18 and b) delay difference model 2 with estimated M=0.20. The plots display the simulated distributions (1000 samples; expressed as a ratio of virgin biomass B_0) around their medians (line in the middle of each box).

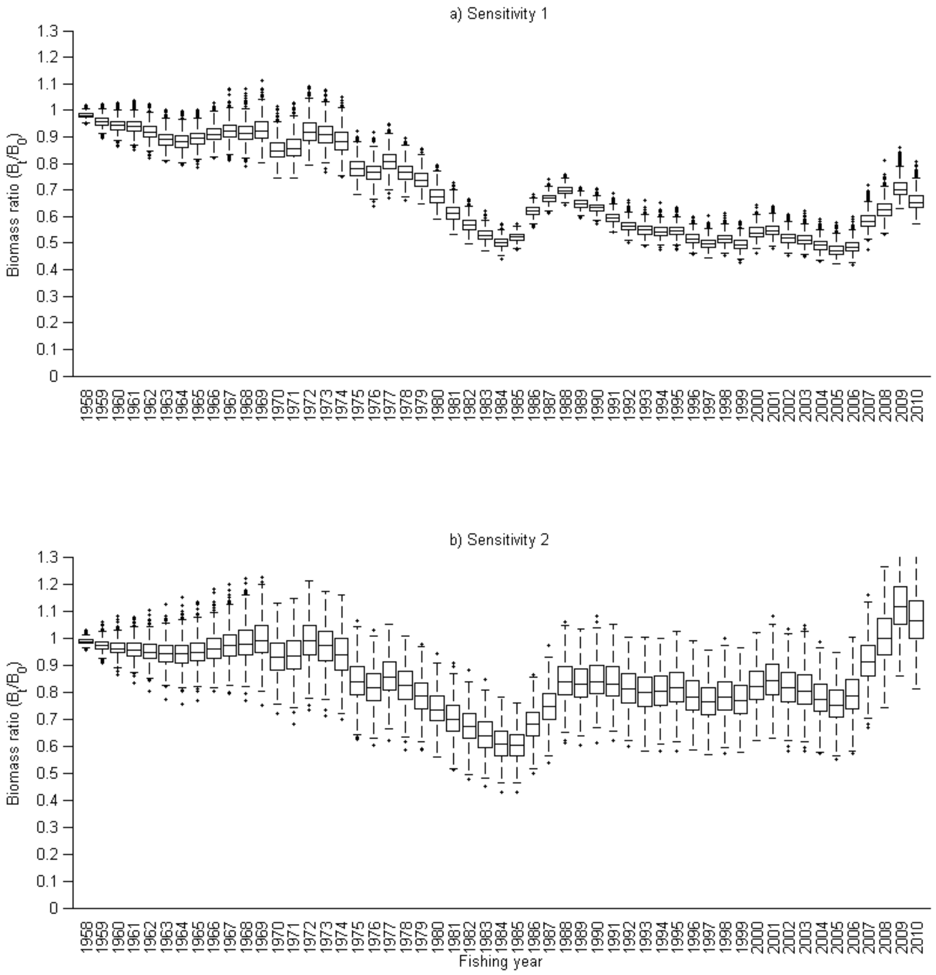


Figure 17-8. Box-plots of estimated yearly change in eastern king prawn exploitable biomass from a) delay difference sensitivity 1 with 30% higher harvest and b) delay difference sensitivity model 2 with lower fishing power. The plots display the simulated distributions (1000 samples; expressed as a ratio of virgin biomass B_0) around their medians (line in the middle of each box).

17.4.2 Maximum sustainable and economic yields

The calculation of reference points for MSY and MEY were based on optimising the population and economic models through fishing mortality ($\propto$ fishing effort). The results were dependent on the specified conditions (Table 17-10 and Table 17-11) and particularly influenced by the assumed monthly pattern of fishing (Figure 17-56, Figure 17-57 or optimised), level of fishing power and economic parameters.

It should also be noted that the fishing pattern for the base case of MEY calculation retained the current number of days fished per vessel ($\bar{d}$), even with a greatly decreased number of vessels. A higher value of MEY was obtained when the number of days per vessel was allowed to increase (see case $2\bar{d}$ below).

In total ten MSY and MEY optimisation groups (Opt) were conducted with the length-spatial model (five combinations of effort patterns by two economic conditions; Table 17-11). The optimisation groups were also replicated: Figure 17-9 for the 2006 – 2010 average number of days fished per boat per year ($\bar{d}$, Table 17-10), and Figure 17-10 for twice ($2\bar{d}$) the 2006 – 2010 average number of days fished per boat per year. Delay difference model MSY and MEY estimates were derived only for status quo management (Opt 1, Table 17-11). This model used fixed "States combined" average economics (Table 17-10) and examined data uncertainties on historical harvest and fishing power. The mean results from all model runs were described in subsections given their intricacy. Error bar widths should be considered along with the mean results.

MSY (Figure 17-9, for comparison with MEY they were replicated in Figure 17-10)

- MSY was about 3200 t and E_{MSY} 44,000 boat-days for Opts 1…4, scenarios 1, 3, 5, and 7.
- MSY was marginally higher when fishing effort was optimised over the winter months (estimated mode = June, and 84% of effort between March and September) and less between October and February. This reduced E_{MSY} to about 34,000 boat-days with higher catch rates; Opt 5 scenario 9.
- E_{MSY} for 3% year^{-1} future increase in fishing power was about 32,000 boat-days with higher catch rates; Opts 6…10.

MEY (Figure 17-9, $\bar{d}$)

- MEY was about 1400 t and E_{MEY} 9000 boat-days for Opts 1…4, scenarios 2, 4, 6, and 8.
- MEY was 1350 t and E_{MEY} 7000 boat-days when fishing effort was spread more evenly across months (estimated mode = June). Catch rates and relative profits were significantly higher; comparing Opt 5 scenario 10 against scenarios 2, 4, 6, and 8.
- MEY was 1500 t and E_{MEY} 8000 boat-days under a 3% year^{-1} future increase in fishing power and trawl costs; Opt's 6…10. Catch rates and relative profits were significantly higher, when comparing Opts 6…10 against Opts 1…4.

MEY (Figure 17-10, $2\bar{d}$)

- MEY was about 2000 t and E_{MEY} 15,000 boat-days for Opts 1…4, scenarios 2, 4, 6, and 8.
- MEY was 2000 t and E_{MEY} 11,000 boat-days when fishing effort was spread more evenly across months (estimated mode = June). Catch rates were significantly higher comparing Opt 5 scenario 10 against scenarios 2, 4, 6, and 8.
- MEY was 2100 t and E_{MEY} 12,000 boat-days under a 3% year^{-1} future increase in fishing power and trawl costs; Opt's 6…10. Catch rates were significantly higher when comparing Opt's 6…10 against Opt's 1…4.

- Differences in relative profit across scenarios were marginal.
- Relative profit was up to twice the value calculated using $\bar{d}$. Fewer boats operating at an individually higher level of capacity utilisation result in lower costs for a given level of catch, and hence higher profits as well as higher optimal total harvest and effort levels.

MEY (Figure 17-11, changing fishing power based on Opt 1 and $\bar{d}$)

- Increasing fishing power reduced the optimum number of vessels and total effort for MEY.
- Increasing fishing power required higher catch rates for MEY.
- If the mean number of days fished per boat per year remained static (status quo $\bar{d}$), increasing fishing power would reduce profit.
- The calculation of MEY was highly influenced by $\bar{d}$. Increasing $\bar{d}$, increased E_{MEY} and profit, but decreased the optimum number of fishing vessels.

MEY$_v$ (Figure 17-12, maximised fishing profit against variable costs; no fixed costs)

- To examine an upper perspective of MEY reference points and to remove the $\bar{d}$ sensitivity, NPV was maximised under variable costs only. The fixed costs represented annual expenses to make a trawl vessel operational, rather than on-water fishing costs, and were removed (Table 17-9 and Table 17-20, 17.9 Supplementary Material 4: Economic data).
- MEY_v was about 2550 t for all optimisations 1 to 4 and 6 to 9.
- E_{MEYv} was 20,000 boat-days under current 2010 variable costs (Opts 1 to 4).
- E_{MEYv} was 15,000 boat-days under increased variable costs and fishing power (Opts 6 to 9).
- Catch rates were higher under increased fishing power and reduced effort, but profit was about 10% less (Opts 6 to 9).

Supplementary MSY and MEY (17.7.3 Supplementary analyses)

- Additional estimates were made from sensitivity analysis in EKP catchability. For this, seasonal patterns in catchability were modelled through a sinusoidal function. This was to compare against the flexible region x month catchability allowed in the above model results.
- In general the estimated values were similar comparing MSY and MEY($\bar{d}$, $2\bar{d}$ and variable-costs-only). The differences to note in fishing efforts were -
- E_{MSY} was less at 38,000 boat-days for Opt's 1…4, 30,000 boat-days for Opt 5 and 29,000 boats for Opt's 6…10 under higher fishing power.

- E_{MEY} was 8000 boat-days under $\bar{d}$ and 7000 boat-days for higher fishing power.
- E_{MEY} was 15,000 boat-days under $2\bar{d}$, and 11000 boat-days for higher fishing power.
- E_{MEYv} was 20,000 boat-days under variable coats only and 14,000 boat-days for higher fishing power.

MSY and MEY (Table 17-18. Supplementary Material 3: Delay difference model 17.8.2; delay difference model based on Opt 1 and $\bar{d}$)

- This simplified model assumed knife edge selectivity at recruitment, spatially aggregated data and dynamics, and prawn-length dependent prices.
- Models 1, 2 and sensitivity 1 estimated equivalent quantities of MSY (≈ 2900 t and 27,000 boat-days) and MEY (≈ 2300 t and 14,000 boat-days).
- The uncertainties of natural mortality and historical harvest were not influential.
- Assumption of low historical fishing power, model sensitivity 2, produced unreliable results. The low fishing catch rate series contained insufficient contrast to estimate R_0 (Figure 17-52) and resulted in large confidence intervals.

MSY and MEY catch rate reference points

Mean catch rate reference points, corresponding to MSY and MEY, were derived for simulating within year monitoring and management of the EKP fishery (Figure 17-13 and Table 17-12). The MSY catch rate indices corresponded to the breakeven point for mean vessel profitability and lower EKP abundance than MEY. The MEY catch rate indices represented two forms: i) EKP catch rates that maximised fishing profit against variable costs (no fixed costs; labelled as MEY_v), and ii) EKP catch rates that maximised fishing profit against variable costs plus fixed costs (labelled as MEY_{vf}; defined by $\bar{d}$). These mean reference points were compared retrospectively against historical standardised catch rates (Figure 17-14). Regionally, the catch rate reference points suggested:

- Consistent profitable catch rates in the last three years across all regions,
- Region 2 catch rates were highly variable to compare against the mean reference points.
- Region 4 catch rates were barely profitable between 1988 and 2006.
- Region 5 catch rates were profitable over all years.
- Regions 1, 3 and 6 catch rates were typically profitable with some marginal years.

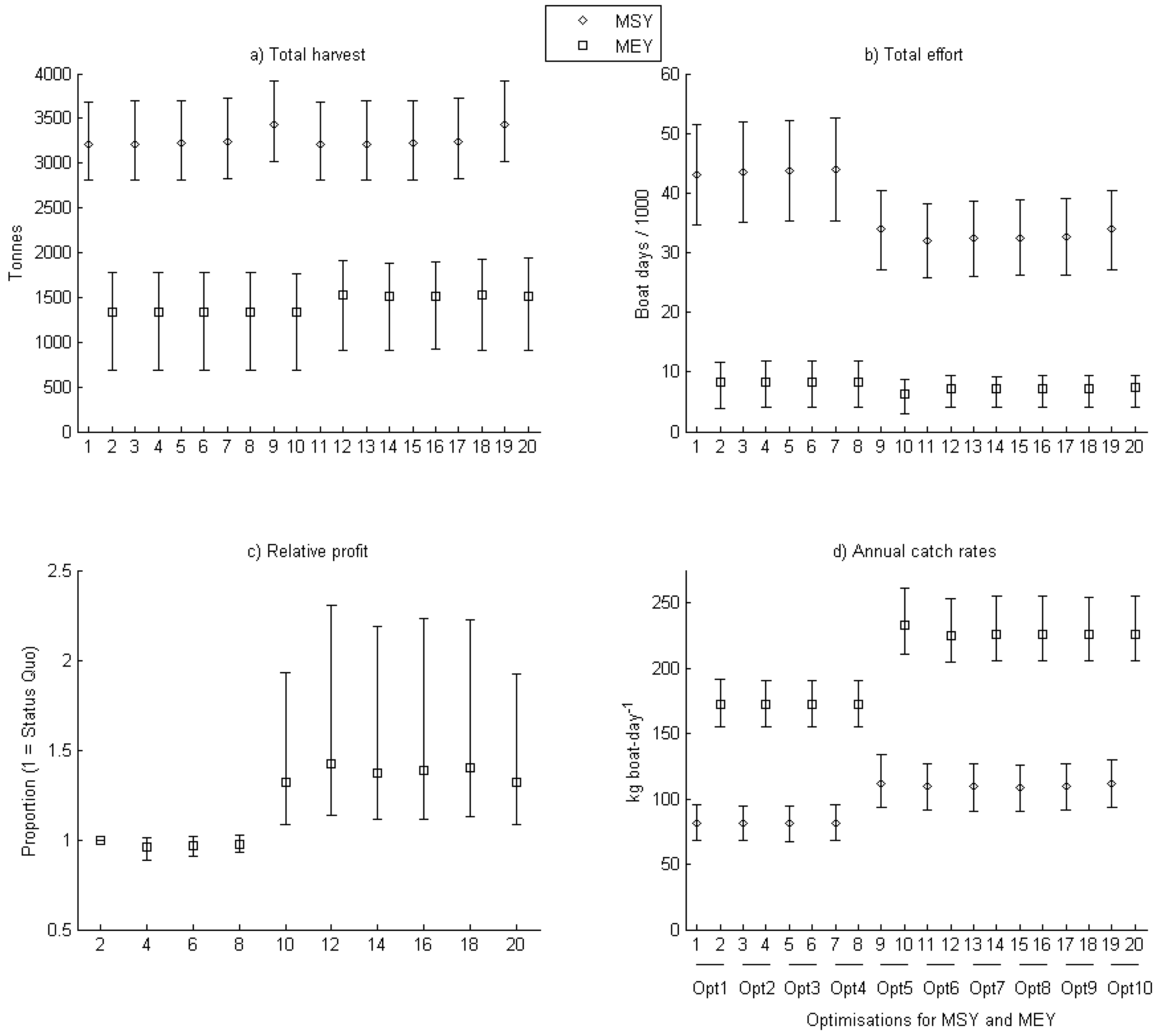


Figure 17-9. Maximum sustainable yield (MSY = diamond symbols) and maximum economic yield (MEY = square symbols) reference points for Australia's EKP fishery (NSW and Qld waters). Every sequential pair of MSY-MEY corresponded to the optimisations in Table 17-11 (e.g. Opt1 = x-axis 1-MSY and 2-MEY, Opt2 = x-axis 3-MSY and 4-MEY, etc.). Figure subplots show a) annual maximum sustainable and maximum economic yields, b) annual maximum sustainable and maximum economic fishing effort, c) annual maximum profit relative to Opt1, and d) annual catch rates corresponding to maximum sustainable and maximum economic yields/efforts. Error bars represent 95% confidence intervals about their mean. The MEY optimisations assumed the economic values and uncertainties in Table 17-10, and the average number of days fished per boat ($\overline{d}$).

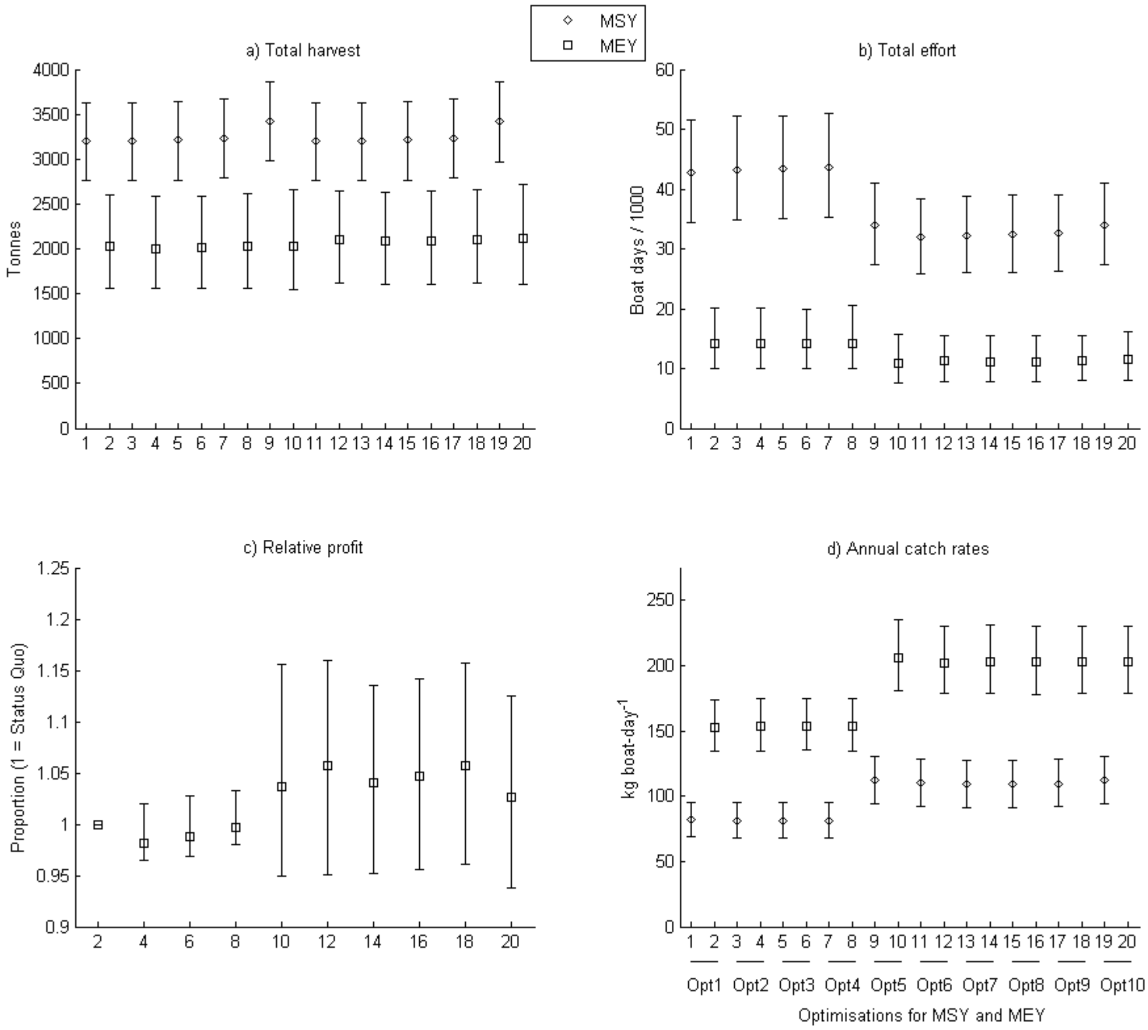


Figure 17-10. Maximum sustainable yield (MSY = diamond symbols) and maximum economic yield (MEY = square symbols) reference points for Australia's EKP fishery (NSW and Qld waters). Every sequential pair of MSY-MEY corresponded to the optimisations in Table 17-11 (e.g. Opt1 = x-axis 1-MSY and 2-MEY, Opt2 = x-axis 3-MSY and 4-MEY, etc.). Figure subplots show a) annual maximum sustainable and maximum economic yields, b) annual maximum sustainable and maximum economic fishing effort, c) annual maximum profit relative to Opt1 and d) annual catch rates corresponding to maximum sustainable and maximum economic yields/efforts. Error bars represent 95% confidence intervals about their mean. The MEY optimisations assumed the economic values and uncertainties in Table 17-10, but twice the average number of days fished per boat ($2\bar{d}$).

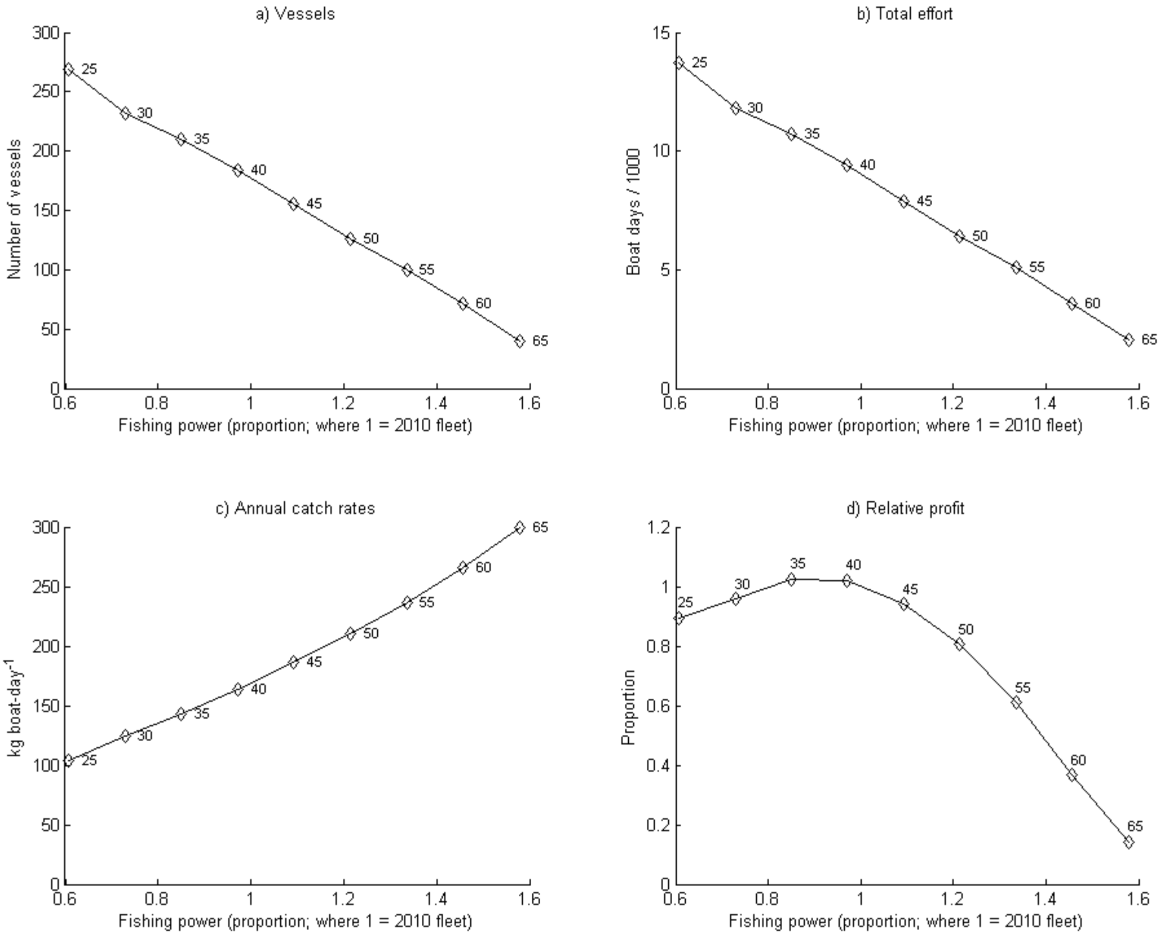


Figure 17-11. Estimated relationships between EKP maximum economic yield and whole-fleet average fishing power for a) number of vessels, b) annual fishing effort, c) annual catch rates and d) profit scaled proportionally against profit for fishing power = 1. The MEY optimisations assumed status quo fishing patterns (Opt1, Table 17-11), the average number of days fished per boat ($\bar{d}$, Table 17-10), and parallel change in economic parameters with fishing power ($\propto$ standardised hull units: SHU) by region (Table 17-21). SHU were annotated for each fishing power data point. Fishing power = 1 represents the 2010 combined New South Wales / Queensland fleet.

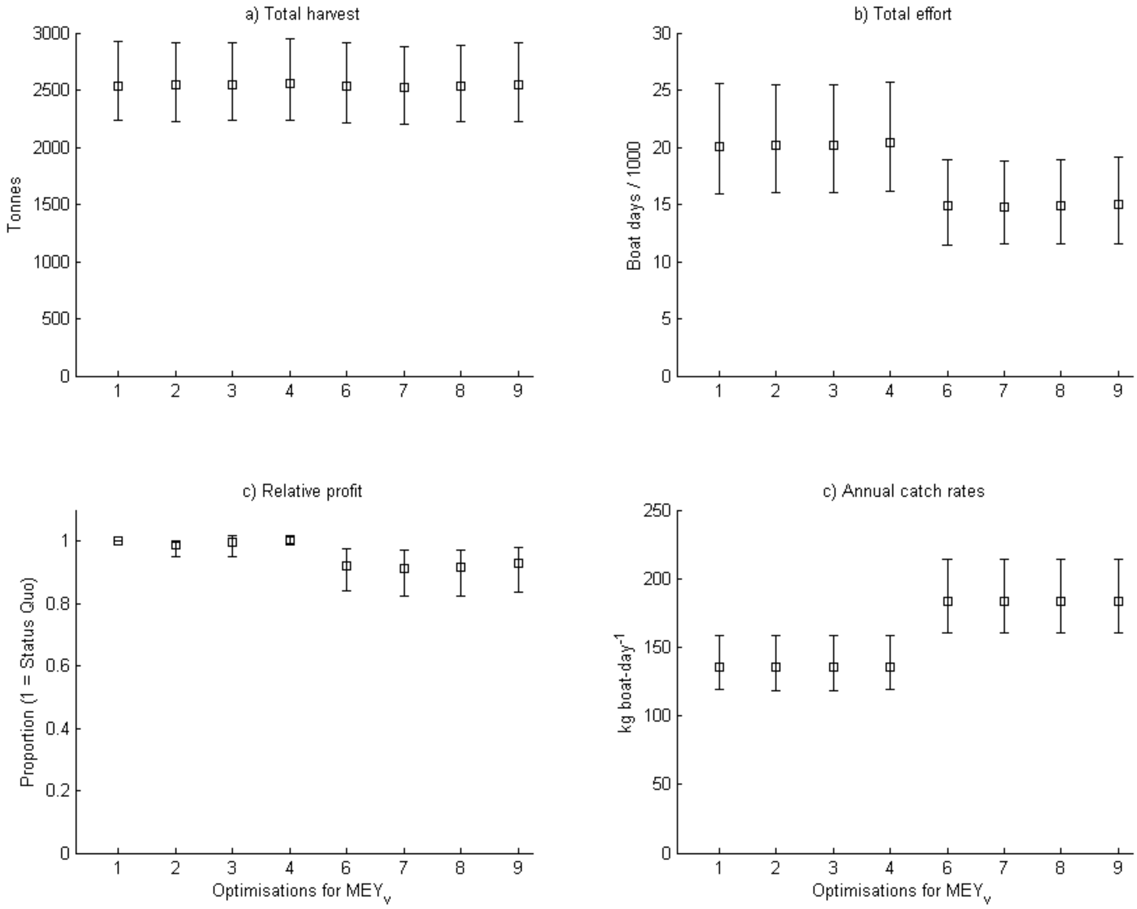


Figure 17-12. Maximum economic yields for Australia's EKP fishery (NSW and Qld waters) under variable costs only (MEY_v). Every sequential MEY_v corresponded to the optimisations in Table 17-11 (Opt 1 to Opt 4 and Opt 6 to Opt 9). Figure subplots show a) maximum economic yields$_v$, b) annual maximum economic fishing effort$_v$, c) annual maximum profit$_v$ relative to Opt 1, and d) annual catch rates corresponding to maximum economic yields$_v$/efforts$_v$. Error bars represent 95% confidence intervals about their mean. The MEY_v optimisations assumed the economic values and uncertainties in Table 17-10 and fixed costs were excluded.

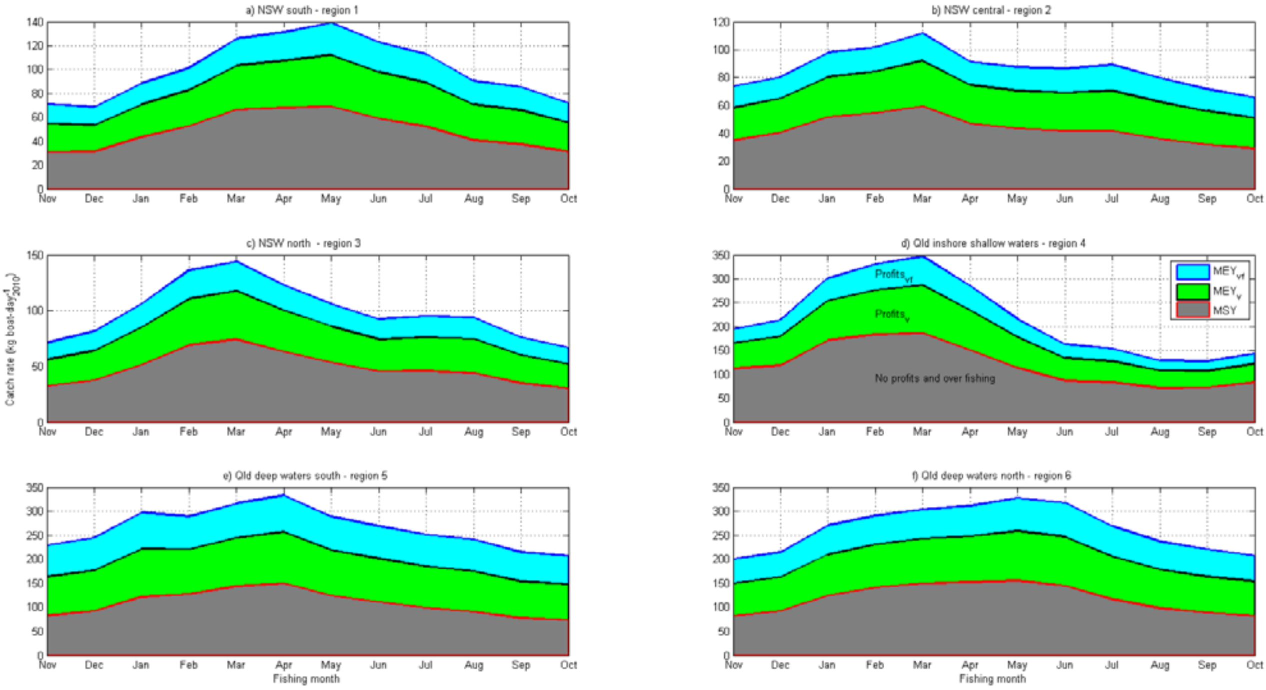


Figure 17-13. Average monthly catch rate targets for maximum sustainable yield (MSY), maximum economic yield for variable costs (MEY_v), and MEY_{vf} for variable costs plus fixed costs by fishing region.

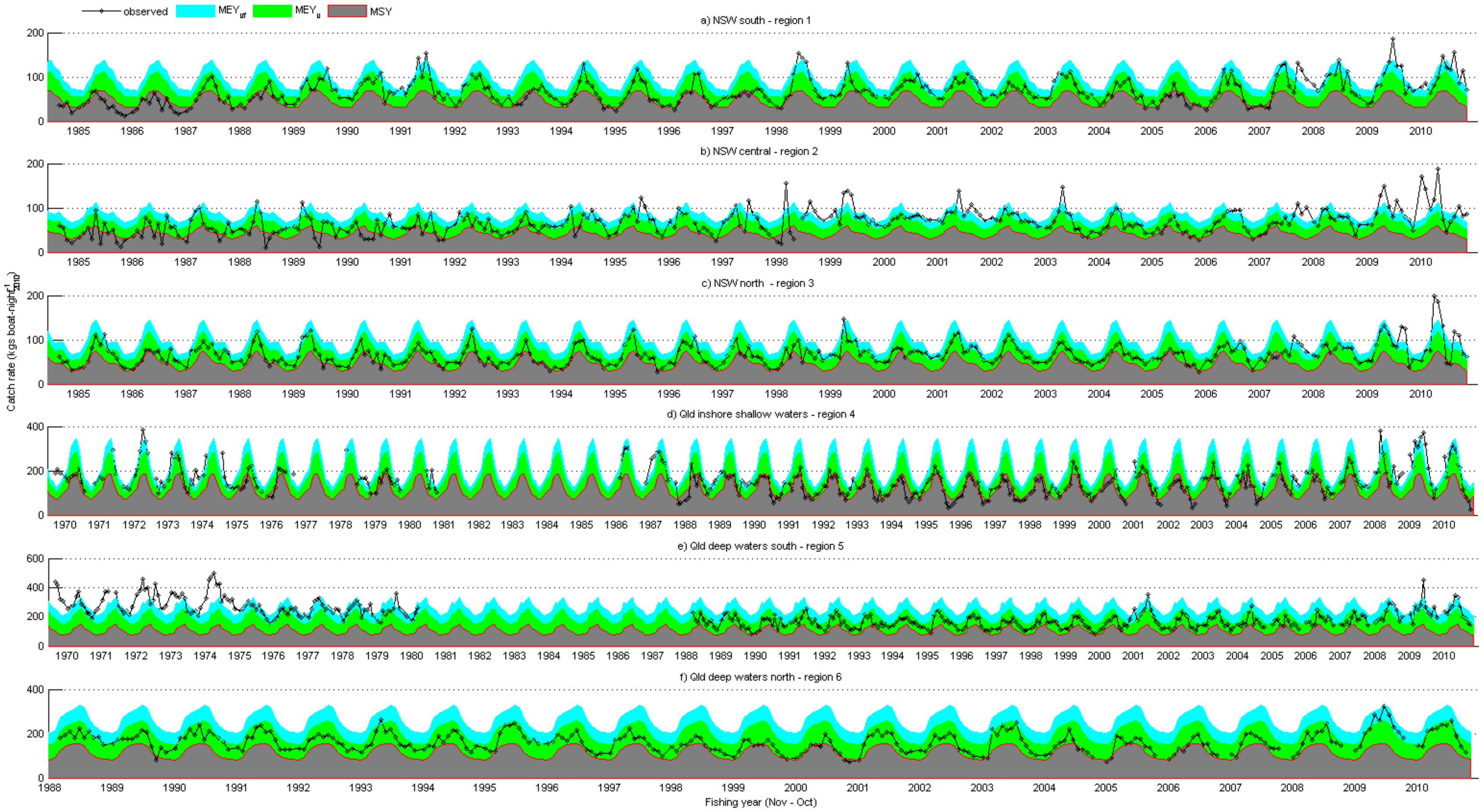


Figure 17-14. Retrospective comparison of standardised catch rates against catch rate reference points (Figure 17-13).

17.4.3 Harvest strategy evaluations

Several different EKP management procedures were evaluated over 10 future years using the length-spatial operating model (Table 17-12). Management procedures 1 to 4 represented status quo total fishing effort and compared alternate one-month regional fishing closures. Procedure 5 contrasted procedure 4 with reduced total fishing effort at E_{MEY}. Procedures 6 and 7 used regional catch rate control rules to manage total fishing efforts of E_{MSY} and E_{MEY} respectively. The management procedures were replicated in two scenario groups: i) 1 to 7 under 2010 fishing costs and fishing power, and ii) 8 to 14 under 3% p.a. increased costs and power. Each scenario was evaluated using six performance measures representing industry functioning, economic conditions, and population change. For management procedures 6 and 7, probabilities of catch rates closing fishing regions were calculated. The EKP median results were summarised as follows (uncertainties represented by box plots):

Management procedures 1 to 4 ($E_{status\text{-}quo}$ ≈ 30,000 boat-days; Figure 17-15, replicated in Figure 17-17)

- There were no significant changes in EKP performance measures (scenarios 1…4 and 8…11), except net present value (NPV) scenarios 8 to 11 declined in order of 20% with increasing fishing costs.
- Expected annual harvests were about 3000 t taken at 110 kg boat-day^{-1}.
- Management via altering regional monthly closures, with status quo fishing effort, resulted in no EKP spawning or biomass increase.

Management procedure 5 (E_{MEY} ≈ 9000 boat-days; Figure 17-15, replicated in Figure 17-17)

- Compared to procedures 1 to 4, there were 40-50% significant increases in NPV, catch rates, spawning and biomass (scenarios 5 and 12).
- Expected annual harvests were halved at about 1550 t from 9000 boat-days. However, catch rates were high at about 160-170 kg boat-day^{-1}.
- Scenario 12 NPV was reduced by increased costs, but still in order of 40% about procedures 1 to 4.
- Management via reduced fishing effort resulted in larger profit but reduced total harvest.

Management procedure 6 (E_{MSY} ≈ 44,000 boat-days and $CPUE_{MSY}$ control rules; Figure 17-15, Figure 17-16a and Figure 17-16c)

- Compared to procedures 1 to 4, there were no significant changes in EKP performance measures (scenarios 6 and 13).
- Annual harvests and fishing efforts were highly variable.
- The probability of closing fishing regions after April (≈ 6 months) was high. The region 4 closure probability was 60% after February. Increasing fishing costs and power did not significantly change the closure probabilities.
- Management via MSY fishing effort and MSY catch rates maintained the EKP population status by reducing the fishing year (≈ June to October closure).

Management procedure 6 (E_{MSY} ≈ 44,000 boat-days and $CPUE_{MEYv}$ control rules; Figure 17-17, Figure 17-18a and Figure 17-18c)

- Compared to procedures 1 to 4 and 6-$CPUE_{MSY}$, there were significant reductions in total fishing harvest and effort. However, NPV, catch rates, spawning and biomass levels were about 30% higher.
- Expected annual harvests were 1950 t, and total effort was managed at about 16,000 boat-days.
- The probability of closing fishing regions after February (≈ 4 months) was high.
- Management via MSY fishing effort and MEY_v catch rates maintained a higher EKP population status by reducing the fishing year (≈ March to October closure).

Management procedure 7 (E_{MEY} ≈ 9000 and $CPUE_{MSY}$ control rules; Figure 17-15, Figure 17-16b and Figure 17-16d)

- Results were similar to management procedure 5, with 40-50% significant increases in NPV, catch rates, spawning and biomass (scenarios 7 and 14).
- Expected annual harvests were halved at about 1550 t from 9000 boat-days. Catch rates were in order of about 160-170 kg boat-day^{-1}.
- The probabilities of regional closures were significantly less compared to procedure 6-$CPUE_{MSY}$. Regions 1, 2 and 4 had about a 20% chance of closure after June. The probabilities were less than about 5% for regions 3, 5 and 6.
- Management via MEY fishing effort and MSY catch rates maintained higher and more profitable EKP population status.

Management procedure 7 (E_{MEY} ≈ 9000 and $CPUE_{MEYv}$ control rules; Figure 17-17, Figure 17-18b and Figure 17-18d)

- The results were similar to management procedure 5.
- This management resulted in the highest catch rates, spawning and biomass (scenarios 7 and 14).
- Expected annual harvests were lowest at 1250 t and effort at 6500 days.
- The closure probabilities were significantly higher from March to October; marginally lower for regions 5 and 6.
- Management via MEY fishing effort and MEY_v catch rates maintained a higher EKP population status by reducing the fishing year (≈ March to October closure).

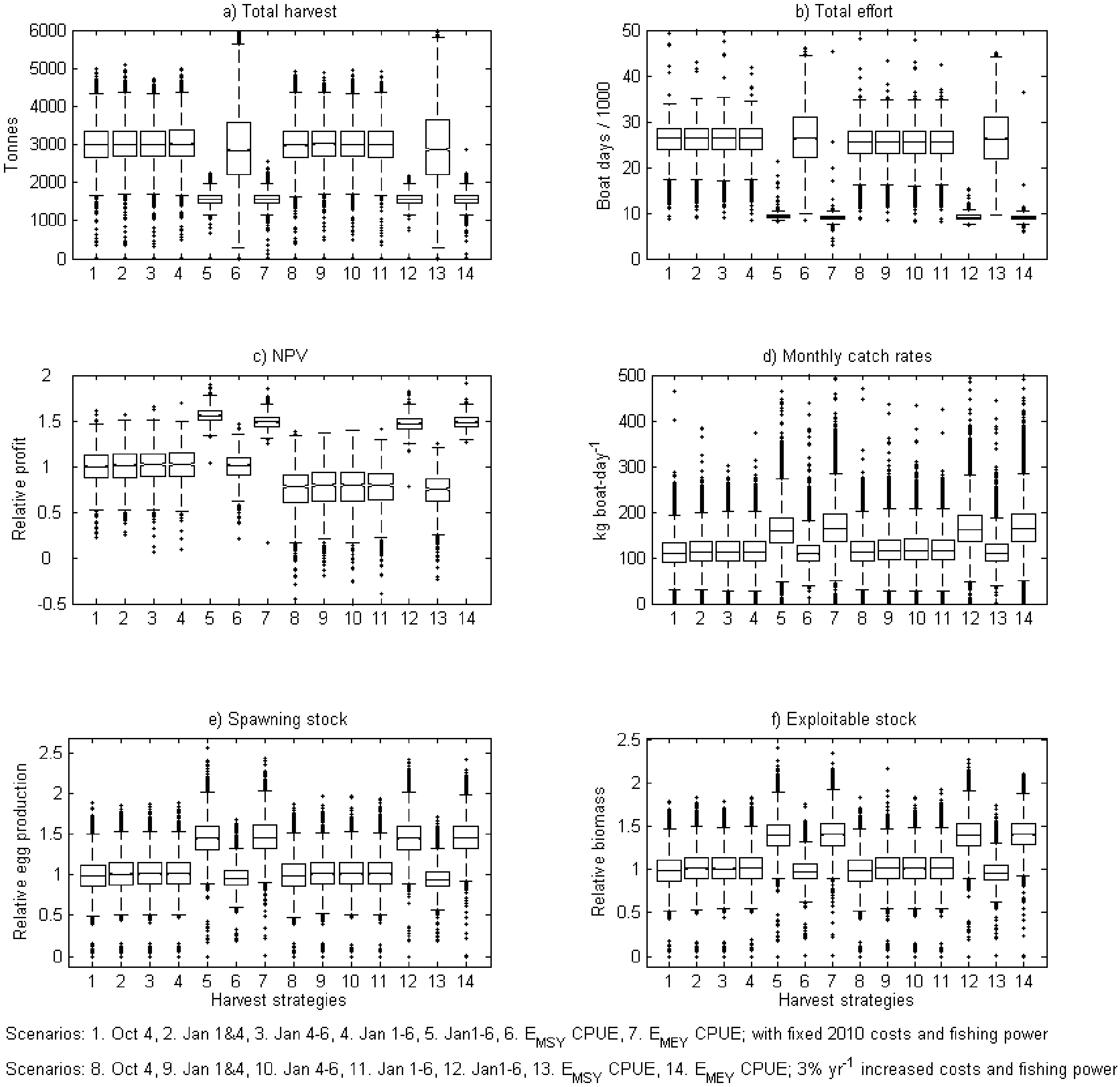


Figure 17-15. Simulation performance measures for each EKP management procedure over ten future years (Table 17-12). The first row of plots a) and b) represented industry functioning, the middle plots c) and d) indicated economic conditions, and the bottom plots e) and f) measured population change. The relative measures in plots c), e) and f) were scaled against strategy 1 (median =1). MSY catch rate limits were used in management strategies 6, 7, 13, and 14. The plots display the simulated distributions (1000 samples) around their medians (line in the middle of each box). The tops and bottoms of each "box" were the 25th and 75th percentiles respectively. Observations beyond the whisker length (≈2.7σ) were marked as outliers.

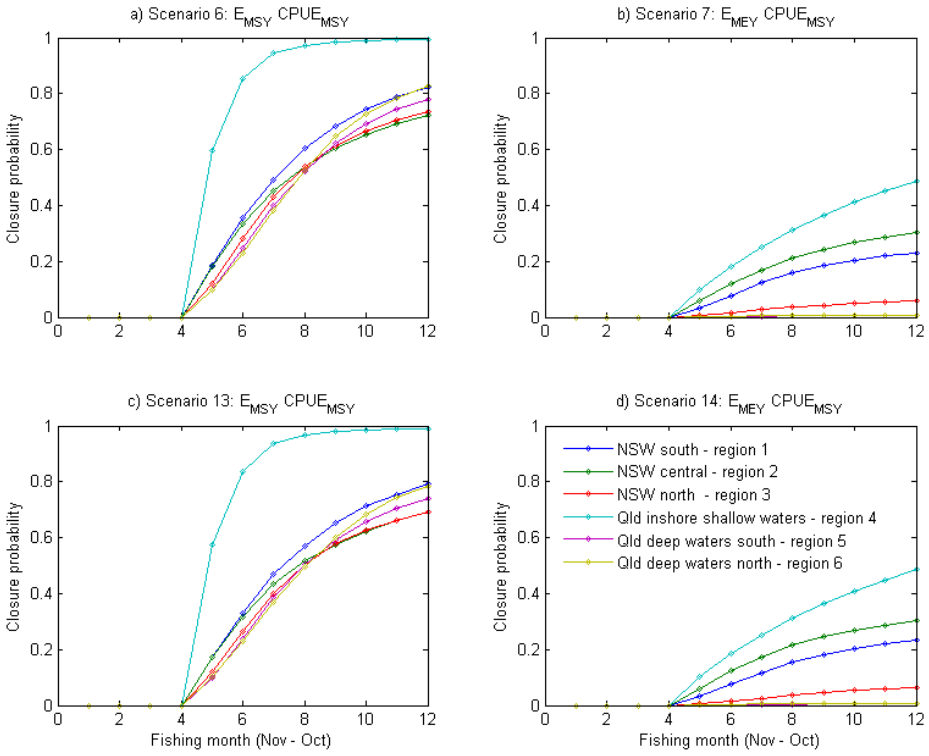


Figure 17-16. Regional closure probabilities for management performance using MSY catch rate limits.

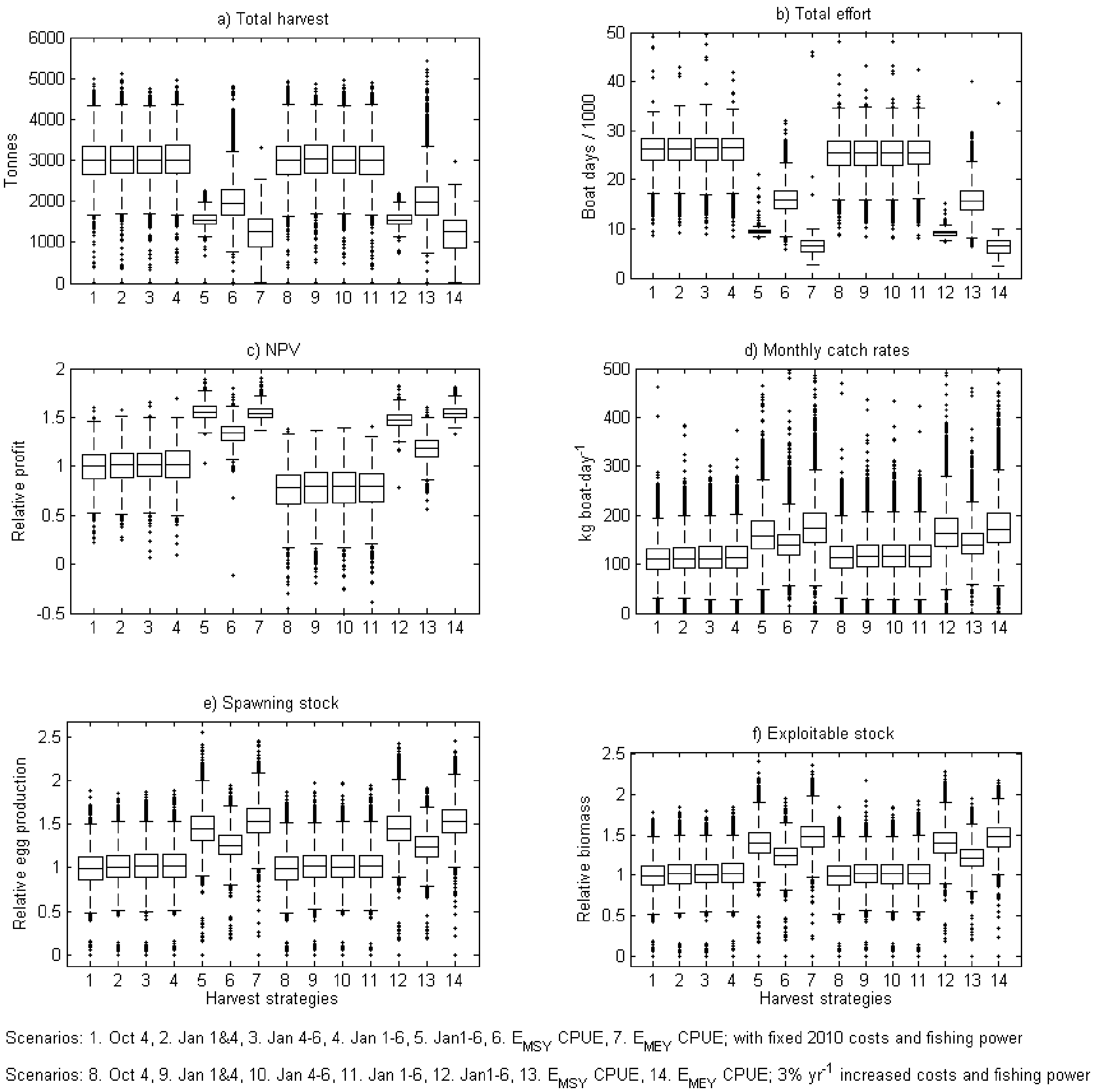


Figure 17-17. Simulation performance measures for each EKP management procedure over ten future years (Table 17-12). The first row of plots a) and b) represented industry functioning, the middle plots c) and d) indicated economic conditions, and the bottom plots e) and f) measured population change. The relative measures in plots c), e) and f) were scaled against strategy 1 (median =1). MEY catch rate limits for variable costs only, based on Table 17-10 and the average number of days fished per boat, were used in management strategies 6, 7, 13, and 14. The plots display the simulated distributions (1000 samples) around their medians (line in the middle of each box). The tops and bottoms of each "box" were the 25th and 75th percentiles respectively. Observations beyond the whisker length (≈2.7σ) were marked as outliers.

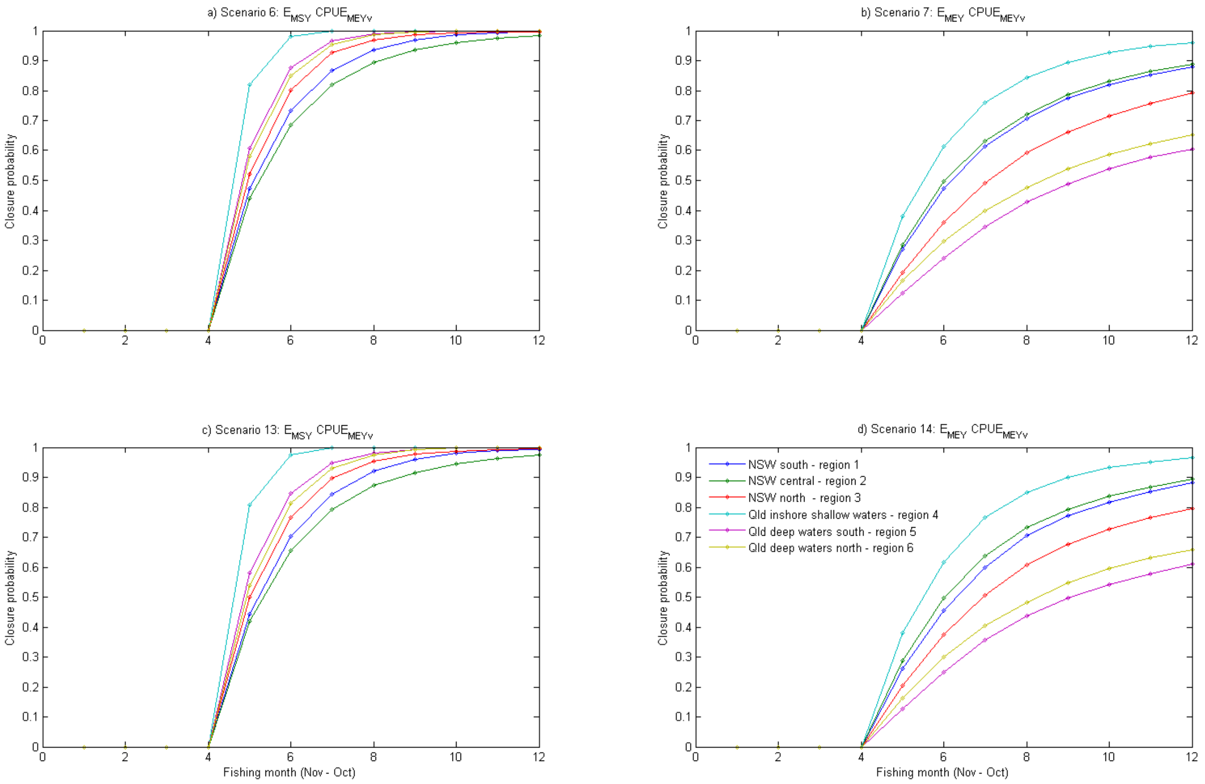


Figure 17-18. Regional closure probabilities for management performance using MEY catch rate limits for variable costs only, based on Table 17-10 and the average number of days fished per boat.

17.5 Discussion

The EKP fishery is a dynamic system in which both the status of the prawn population and operational economics were of research focus for management. The results followed on from O'Neill *et al.* (2005) where the EKP fishery was assessed as a whole stock across state borders. The modelling results provided useful information on how this fishery and others may improve bioeconomic conditions. This included procedural elements from data requirements and assessment techniques to reference points and management actions. These aspects are fundamental to fisheries science and management worldwide. For EKP, the procedural components were successfully linked in quantitative simulations including both population and economic uncertainties. The results outlined management paths to ensure sustainable and more profitable fishing of the stock in the future.

Reference points

Simulation of EKP fishery dynamics and management procedures identified spawning egg production (S) and exploitable biomass (B) ratios were above reference limits of 50% virgin S_{1958} and 40% virgin B_{1958}. MSY was estimated to range between 2800 t and 3200 t. Fishing effort E_{MSY} was uncertain ranging from 44,000 to 27,000 boat-days dependent on model selection, within-year regional fishing patterns and assumed fishing power. Assuming continued static management roughly every decade and strong change in fishing power, E_{MSY} should be considered to fall in the range 27,000 to 32,000 boat-days per year. These values were similar to the ranges estimated by O'Neill *et al.* (2005). The uncertainty surrounding the value of E_{MSY} was not unusual for a fishery stock assessment. The result confirmed that target fishing effort should not approach these limits under consideration of higher risks of over fishing and lower profitable catch rates (Garcia and Staples 2000).

The reduced economic conditions have now focused industry and management on the theory of fleet-based maximum economic yield (MEY), rather than maximum sustainable yield (MSY). The MEY policy was first introduced into Australian government fisheries in 2007 (Australian Government 2007). The state-based management agencies for the EKP fishery have now requested MEY estimates. EKP MEY estimates were strongly influenced by the reported high costs (variable and fixed) of fishing, the assumed average number of days fished per vessel year ($\bar{d}$) and fishing power. The MEY ranged between 1400 t and 2100 t and E_{MEY} ranged between 9000 and 14,000 boat-days. The interaction between cost parameters and fishing power was intricate, but suggested less than 175 vessels (for the NSW and Qld fishing fleets combined) were required for MEY; assuming $\bar{d}$. Higher $\bar{d}$ significantly increased profit, but reduced the optimum number of vessels. For MEY_v (estimate for MEY under variable costs only), estimated tonnages were higher at 2550 t and E_{MEYv} between 15,000 and 20,000 boat-days per year.

As typically found, the estimates of MEY were substantially less than MSY. Grafton *et al.* (2007) state that higher fishing costs and/or lower product prices decrease the ratio of MEY to MSY. The EKP ratio of MEY to MSY, assuming $\bar{d}$, was surprising low. This was due to the high costs, particularly the annual fixed costs, listed in Table 17-10. For a combined-state average vessel, about 83 kg boat-day^{-1} of EKP was required to cover variable (on-water) fishing costs only. This increased dramatically to 154 kg boat-day^{-1} in order to cover both variable and fixed costs. The catch fell to 118 kg boat-day^{-1} assuming $2\bar{d}$. These calculated catch rates for breakeven cost–profit further illustrate the sensitive nature of assumptions and equations used to estimate MEY.

Wang and Wang (2012) questioned the equations and whether fleet-based MEY objectives were beneficial to Australia's large trawl fleets. The policy may significantly reduce the number of boats and business operations exploiting a fishery resource. Wang and Wang (2012) questioned whether labour costs should be deducted and proposed a modified revenue function that included shadow profits for balancing fleet-based MEY with some broader socio-political perspectives. They estimated 70% higher E_{MEY} using the broader function compared to the standard theory herein. If a broader MEY perspective was considered by management, annual fishing efforts up to E_{MEYv} should be viewed carefully against higher fishing costs and power. Dichmont *et al.* (2010) also comment that changed assumptions for data and calculations can result in different and equally valid MEY. To make MEY operational in a fishery, a set of consistent assumptions must be agreed to and strong commitment from industry must be attained (Dichmont *et al.* 2010).

Theoretical debate still exists over MEY. There are concerns of monopolistic or oligopolistic fishery behaviour (Bromley 2009). Only a small united fleet or a sole owner of a fleet in a fishery would be concerned with maximising true fleet-based MEY profits (Bromley 2009). MEY is higher when considering social and market-processer value chains (Christensen 2010). Also, are the incentives of individual fishing vessels consistent with maximising profit for a fleet with many vessels? Alternatively, high catch rate and ecological benefits of MEY are strong. It is also not conceivable that the costs of higher fishing effort can be shared along the value chains; simulation of this effect may in fact reduce MEY away from MSY (Sumaila and Hannesson 2010). Decision makers should consult the literature further on this discussion. Future review of EKP management should consider the uncertainty and assumptions around the value of MEY.

Management procedures
Of the EKP simulations, management procedure 7 using E_{MEY} and $CPUE_{MSY}$ performed the best; followed closely by management procedure 5. EKP fleet profit, catch rates, spawning egg production and biomass were all significantly higher than status quo. They were robust under future increases in fishing costs and power. Catch rate control rules were effective under E_{MEY}. However, they were less effective under high E_{MSY}, where the control rules successfully reduced effort but caused uncertain harvest and high probability of closing fishing regions mid-year. This unwanted management performance was corrected under E_{MEY}. $CPUE_{MSY}$ was an appropriate trigger point given catch rate observation uncertainties. Under higher fishing effort (>9000 boat-days), the baseline settings of the catch rate trigger ($CPUE_{trigger}$) were more critical. If kept at $CPUE_{MSY}$ or less, higher fishing effort would not be correctly constrained. If the catch rate trigger was increased to towards $CPUE_{MEYv}$, effort management improved but at the cost of shorter fishing seasons. The setting of the $CPUE_{trigger}$ required balancing historical knowledge of the fishery, where and when prawns were abundant and data/opinion on profitable catch rates (Figure 17-13). This catch rate control rule was dependent on up-to-date electronic data collation of each vessel's daily catch rates and fishing power variables. Modernisation of onboard catch reporting data systems should be of high priority to improve data quality and completeness, and reduce administration time and costs.

The State Governments manage their respective EKP sectors independently through a range of input controls. In 2010 a total of about 600 vessels were licensed to fish EKP. Between 2006 and 2010 about 350 vessels were active and fished 20,000 to 30,000 boat-days annually. Analysis of these vessel and effort numbers produced suboptimal profit for the fleet as a whole. Simulations demonstrated that reduced vessel numbers and fishing effort were the most effective management changes to improve fleet profit. Even so, these controls alone may not always safeguard against unpredictable situations or issues. Monitoring regional changes in fishing effort should be done carefully given hyperstability bias caused by temporal changes in fishing power (catchability), and where and how vessels fished. Seasonal patterns in latent fishing effort should be minimised. Analysis showed that the one-monthly spatial/seasonal closures were not important. However, the estimated seasonal patterns of fishing suggested more focus on larger prawns over the autumn and winter months than late spring and summer. Spatial/seasonal closures should still be considered for improving future profit, reducing risk of over fishing, industry downtime and minimising capture of small prawns (i.e., reducing growth overfishing risk).

Modelling of seasonal fishing patterns showed that E_{MEY} focused more evenly on the months around June would avoid excess capture of small EKP (minimise growth overfishing) and increase profit for the fleet as a whole. However, under scenarios of E_{MSY} or status quo fishing effort, growth overfishing was more likely. For example, the MSY and MEY optimisations number 5 (Figure 17-9, x-axis results 9 and 10 for estimated seasonal pattern of fishing assuming $\bar{d}$) showed that the overall harvest and profit would be increased by shifting effort towards the winter months and less between October and February. That is, fishing effort shifted away from the capture of smaller sized prawns. This result was consistent for all regions. Figure 17-10 (x-axis MEY result 10 assuming $2\bar{d}$) implied that if boat numbers were further reduced for E_{MEY}, then the seasonal pattern of fishing was less important for profit and the likelihood of growth over fishing was further reduced. Thus, the issue of growth-overfishing is a difficult multivariate problem, particularly when the seasonal population and economic dynamics were taken into account. Management of fleet vessel numbers, total effort, effort patterns and gear technology could be optimised to address issues of growth overfishing (NSW Department of Primary Industries 2010). In addition, an analysis of the value of harvesting EKP in estuaries or Bays should be undertaken to assess the likelihood of growth overfishing. An additional analysis addressing potential growth overfishing in the northern part of the fishery is presented in Section 18 Appendix 6. Yield and value per recruit assessment of the proposed North Reef closure on eastern king prawns.

Models and data

The stock analyses presented were the most comprehensive attempt to evaluate the population and economic status of eastern king prawns. The model assessments were monthly and captured the regional and seasonal patterns in biology and fishing. They also included estimates of historical fishing power, harvests and catch rates prior to compulsory catch reports. The longer assessment time-series, compared to O'Neill *et al.* (2005) and Ives and Scandol (2007), resulted in more accurate estimates of EKP productivity. The estimated spawner-recruitment parameters were critical to determine the status of the EKP fishery. The assessments assumed EKP standardised catch rates were proportional to abundance. Overall the analyses facilitated critical assessment of the stock allowing for regional and seasonal intricacies. Although the best available data were used in the EKP analyses, the uncertainties of some model inputs should be noted.

The pre-specified movement transition matrix represented the northward deeper-water movement process of EKP. The setting of EKP movement allowed the spatial-length model to predict regional population and economic dynamics. However, the matrix's fixed year-to-year nature may somewhat inhibit model fits to the calibration data; probably more so for the carapace length frequency data. Also, the regional recruitment parameters and outputs were sensitive to the matrix's pattern. Further work is required to develop the matrix's covariance structure. This would provide the model more movement flexibility and define uncertainty subject to a prior likelihood constraint.

The primary assumption in the modelling was that the Queensland voluntarily-recorded pre-1989 EKP catch rates were standardised suitably against post-1988 catch rates. The pre-1989 catch rates provided crucial contrast to model change in EKP abundance between 1958 and 2010. Without this contrast, model outputs would be less certain; as reported for delay difference model sensitivity 2 (Table 17-18) and O'Neill *et al.* (2005). The Queensland pre-1989 catch rates were constructed from 34,509 daily records (Figure 17-21), reported from 350 different vessels. Each year these data covered between 10–26% of the Queensland East Coast licensed trawl vessels; 700 vessels were licensed in 1974 and 1400 in 1980 (O'Neill and Leigh 2006). From 1969 to 1979 an average of 320 t of EKP were voluntarily recorded in logbooks each fishing year. To standardise pre-1989 catch rates to the 2010 fleet fishing power, characteristics of the 1970–1980 vessels were considered. Table 17-13 showed how vessels have increased their fishing capacity. The increase in standardised hull units from the 1970's to 2010 was 56%. The estimated increase in fishing power from 1989 to 2010 was between 40% and 60% (Braccini *et al.* 2012a). The pre-1989 catch rates were standardised equivalent to 56% fishing power increase. The fundamental issue underlying the assumed fishing power increase was representativeness of the pre-1989 catch rates. The sensitivity of upwards bias (higher catching vessels providing data and/or over correction of fishing power) was tested in the delay difference model. Low adjustment of fishing power (36%) produced a higher estimate of MSY with very wide confidence intervals (sensitivity 2, Table 17-18). The assumed estimates of fishing power (56%) produced estimates of MSY close to the recorded maximum annual harvests (Figure 17-2) and relatively narrow confidence limits. Higher adjustment to fishing power (to consider downward bias with lower catching vessels providing data and/or under correction of fishing power) may also be plausible but was not justified in this work; the sensitivity effect of higher fishing power was generally lower E_{MSY} (O'Neill *et al.* 2005). Further work is required to verify historical pre-1989 standardised catch rates and fishing power. The uncertain total harvest history was also assessed though the delay difference model. Estimates were not overly sensitive to the uncertainty.

Table 17-13. The Queensland EKP fleet average vessel characteristics for a) the 1970s, compared to b) vessels at the start of compulsory logbook catch reporting and c) the fishing power year catch rates were standardised. The summaries of average vessel data were sourced from Braccini *et al.* (2012a), O'Neill *et al.* (2005) and O'Neill and Leigh (2006).

Average vessel features	**a) 1970-1980**	**b) 1989**	**c) 2010**
Length (m)	15	16	17.5
Standardised hull unit (SHU)	32	41	50
Engine rated power (HP)	150-200	230	350
Fuel capacity (l)	5000	10000	22000
Trawl speed (kn)	2.3	2.4	2.7
Triple or quad gear (% vessels)	25-50	90	100
Total net head rope length (fm)	15-22	30	33
Flat otter-boards (% vessels)	100	95	65
TED/BRD (% vessels)	0	5	100
GPS (% vessels)	0	20-40	100

An important output from modelling the EKP population was the relationship between annual spawning (i.e., egg production) and the following year's recruitment (i.e., the number of new EKP entering the offshore fishery). This relationship defined the effect on recruitment of reducing the spawning stock through fishing (Figure 17-19). To conduct a management strategy evaluation and estimate reference points for EKP, a spawner-recruitment relationship was estimated (virgin recruitment parameters $R_{0,r}$ and steepness h). A number of prawn fisheries throughout the world have shown that the level of recruitment was strongly related to the size of the parental population (the spawners). Ye (2000) conducted a meta-analysis of 13 Penaeid prawn fisheries to test the hypothesis that recruitment was a random process. His analysis rejected this hypothesis, and showed that recruitment was related to spawner abundance and concluded that prawn populations should be managed to maintain sufficient spawning stock abundance to yield high recruitment. For EKP, stock steepness was estimated at 0.38 (Table 17-14). In comparison, the prawn stocks analysed by Ye (2000) typically had steepness less than 0.5. In Australia's Northern Prawn Fishery, steepness was low and ranged 0.26 to 0.36 for their two species of tiger prawns (Dichmont *et al.* 2001). The Torres Strait tiger prawn steepness was 0.46 (O'Neill and Turnbull 2006). For EKP, the estimated recruitment steepness was informed by the decline in Queensland EKP catch rates from 1970 to mid 1980's and the increase in catch rate from 2006 to 2010. Further work is required to verify historical pre-1989 EKP standardised catch rates and steepness. Previous analyses of EKP steepness compared values of 0.56, 0.4 and 0.37 and showed management implications of lower E_{MSY} with lower steepness (O'Neill *et al.* 2005).

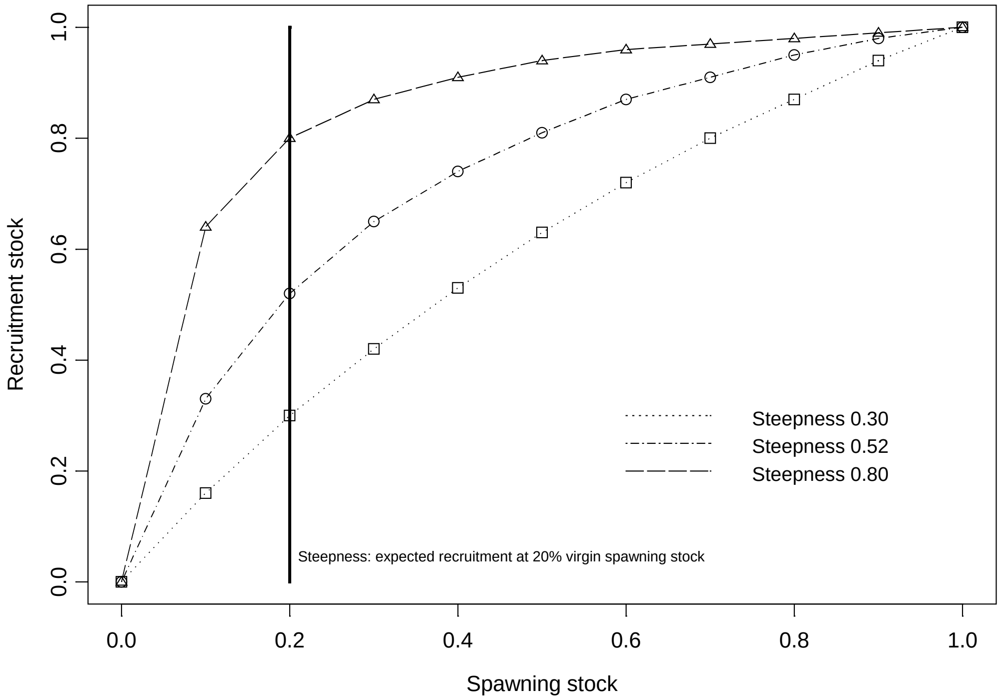


Figure 17-19. Illustrative Beverton-Holt spawner-recruitment curves with different steepness. Virgin spawning and recruitment stock sizes were equal to 1, with the figure scaled proportionally. Solid vertical line defined steepness as the expected recruitment at 20% of virgin spawning stock. Stocks with high steepness tend to have high resilience to fishing; stocks with low steepness have lower resilience to fishing and can exhibit a gradual fish-down effect over time.

The stock assessments relied heavily on the trends in standardised catch rates, fishing power and economics. The key requirement for future analyses was up-to-date and complete fishing power data for each vessel from NSW and Qld. At the time of this research, the recording, maintenance and verification of these data through fishery logbooks were not up to standard. Enforcement of logbook compliance, government data management and modernisation is required now and should have high priority. If this is not undertaken, future stock assessments risk using unreliable indices of abundance and resource assessment demotion from A to C (under the Queensland Government stock status reporting criteria; see also NSW criteria in NSW Department of Primary Industries (2010)). Further, the availability and use of Vessel Monitoring System (VMS) data is required to improve daily effort and catch rate measures (hours, area and locations trawled). In addition for NSW, logbook discrimination of EKP fishing effort is required to improve catch rate indices (see Supplementary Material 1: Model data, 17.6.4). Predictive VMS models of the seasonal and spatial dynamics of trawling were required for further evaluation of regional management procedures.

The economic data were treated as representative after comparison with basic fleet descriptors and other fisheries, and after steering committee review. To enable future economic evaluations, time-series collations of prawn price and costing data are required in a readily available electronic form. This would reduce collection costs and ensure accurate coverage of New South Wales and Queensland vessels. The economic data were important for model projections and monitoring within-year catch-rate profitability. The list of which economic variables to include for EKP will change in future work, depending on their accuracy, variability and MEY assumptions (Dichmont *et al.* 2010).

Conclusion

This research has described a new assessment model and evaluated more profitable management procedures for the eastern king prawn fishery. It has also described the conditions to set within-year catch-rate harvest control rules. All the management procedures evaluated were simple to follow and directly adaptable for new EKP management. Financial conditions are currently difficult for industry and government alike. This should not prevent new management decisions. If future finances limit EKP monitoring accuracy, then more precautionary interpretation of results should be considered. This is because of the increased uncertainty of sustainable and profitable fishing with lesser data knowledge. The EKP stock was assessed as healthy in 2010. However, the key management change for increased fishery profit was to reduce fishing effort to between 9000 and 20,000 boat-days a year over New South Wales and Queensland waters. The actual value to set will depend on considerations of model uncertainties and government/industry positions. If the current costs of fishing remain steady or increase, fishing effort above 20,000 boat-days will be less profitable. The research has provided evidence for a combined-State monitoring-assessment-management approach for EKP. The State Governments and industry should establish a formal multi-jurisdictional management framework and enhance multiagency stock assessment for EKP, which is one of the most valuable commercially fished resources on Australia's east coast. The joint framework would save and share financial resources. It would also better inform stakeholders and the public on management's triple bottom line of economic, ecological, and social success.

17.6 Supplementary Material 1: Model data

17.6.1 Map of the EKP fishing regions

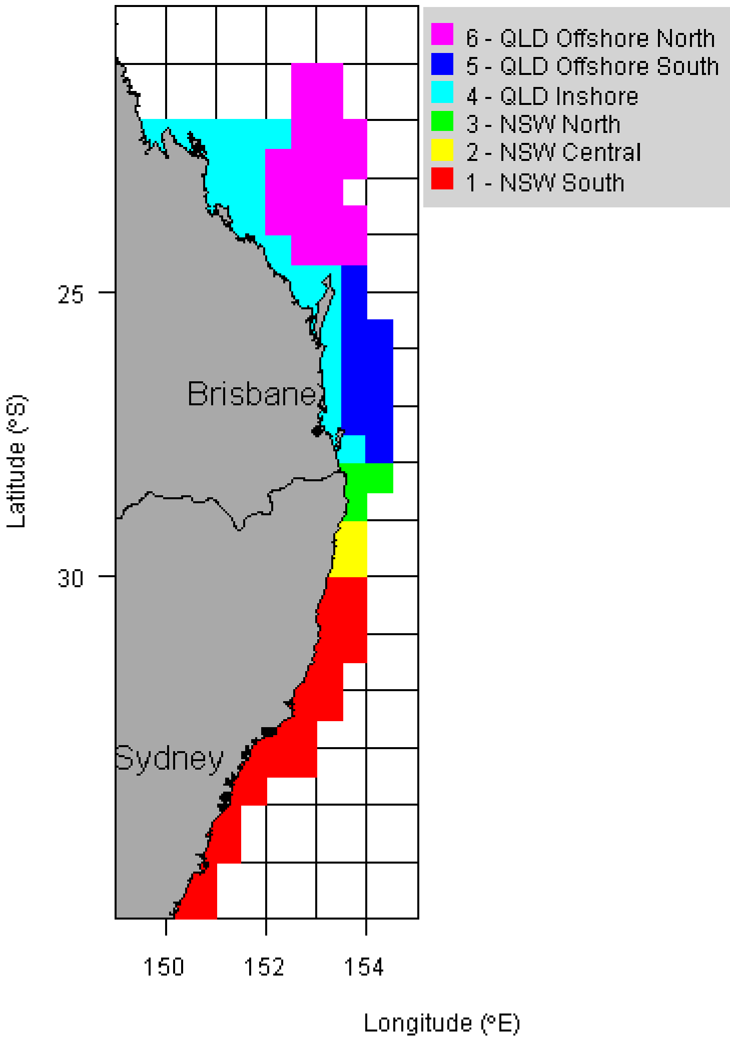


Figure 17-20. EKP stock regions.

17.6.2 Queensland pre-1989 EKP catch rates

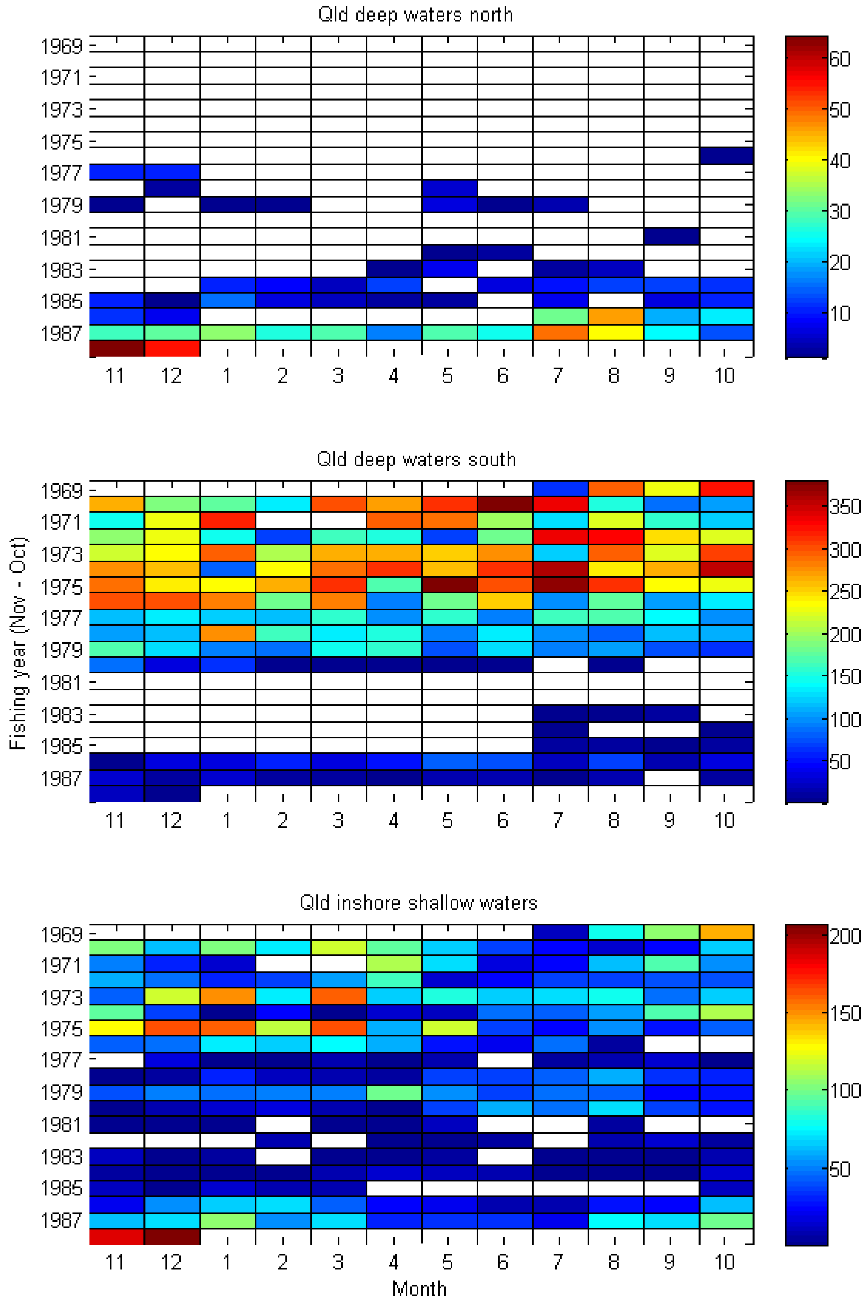


Figure 17-21. A gridded (fishing year by calendar month) colour plot of HTrawl data frequency for eastern king prawns from a) Queensland deep waters north = region 6, b) Queensland deep waters south = region 5 and c) Queensland inshore shallow waters = region 4. Colour bars indicate the number of vessel daily catches present for catch rate analysis, with white cells indicating no data. Sample sizes for a = 804, b = 25,237 and c = 8468, with total n=34,509 vessel daily catches.

17.6.3 Queensland EKP harvest patterns 1958 to 1988

Figure 17-22 illustrates the region by month harvest patterns used to expand Qld EKP landings from 1958 to 1988. The GLM assumed a Poisson distribution with log-link and region x month + region x year interactions. The model F-statistics for the two-way interactions were F = 7.4 and F = 17.3, respectively ($p<0.001$). The model adjusted $R^2 = 0.64$. Residual patterns supported the model structure and distribution (Figure 17-23); one data outlier was noted (region = 4, year = 1988, month = January).

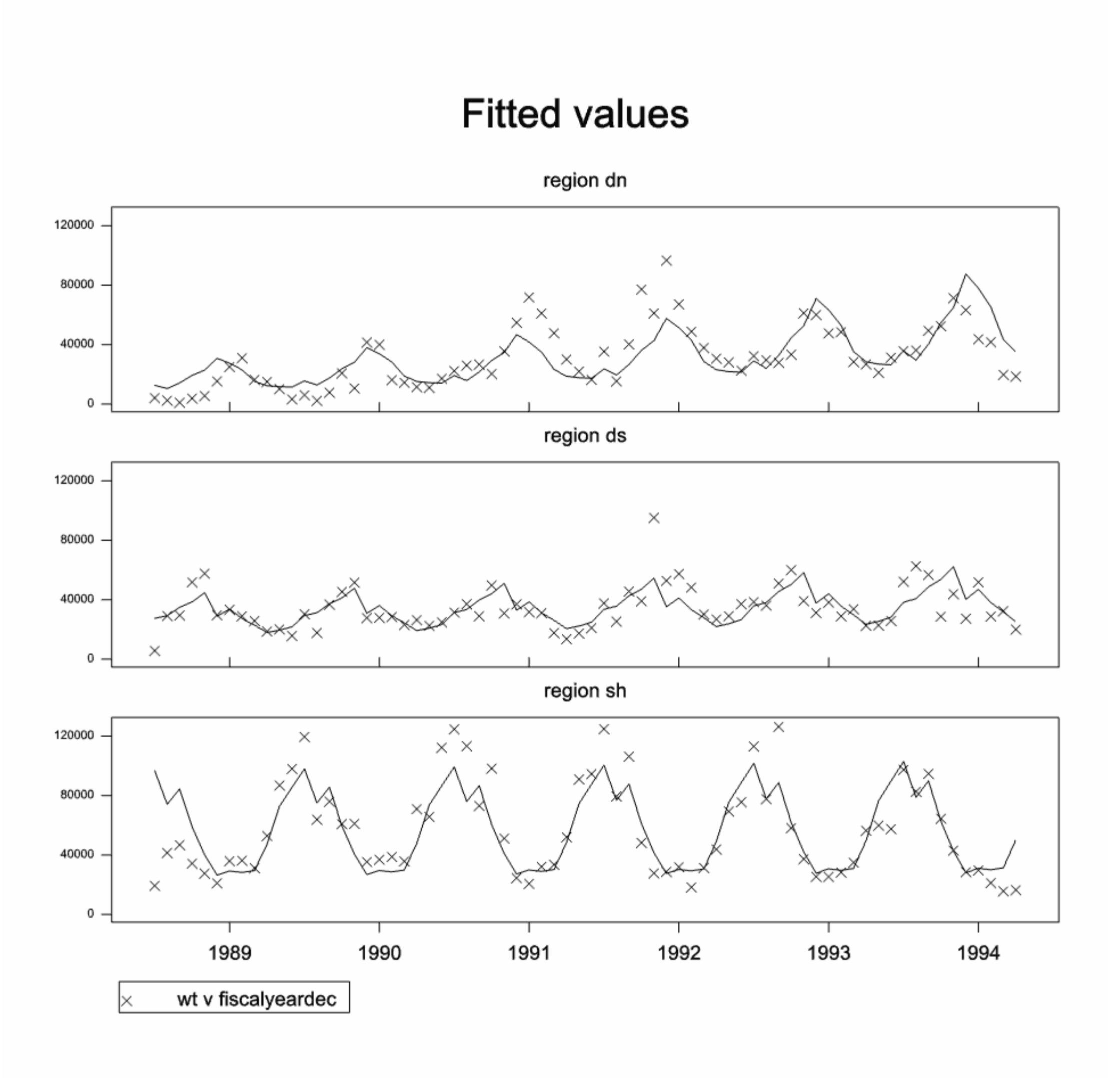


Figure 17-22. GLM fitted vs. observed Qld EKP harvest patterns from 1988 to 1994. Y-axis wt = kgs; X-axis fishing years and months; sh = region 4, ds = region 5, dn = region 6.

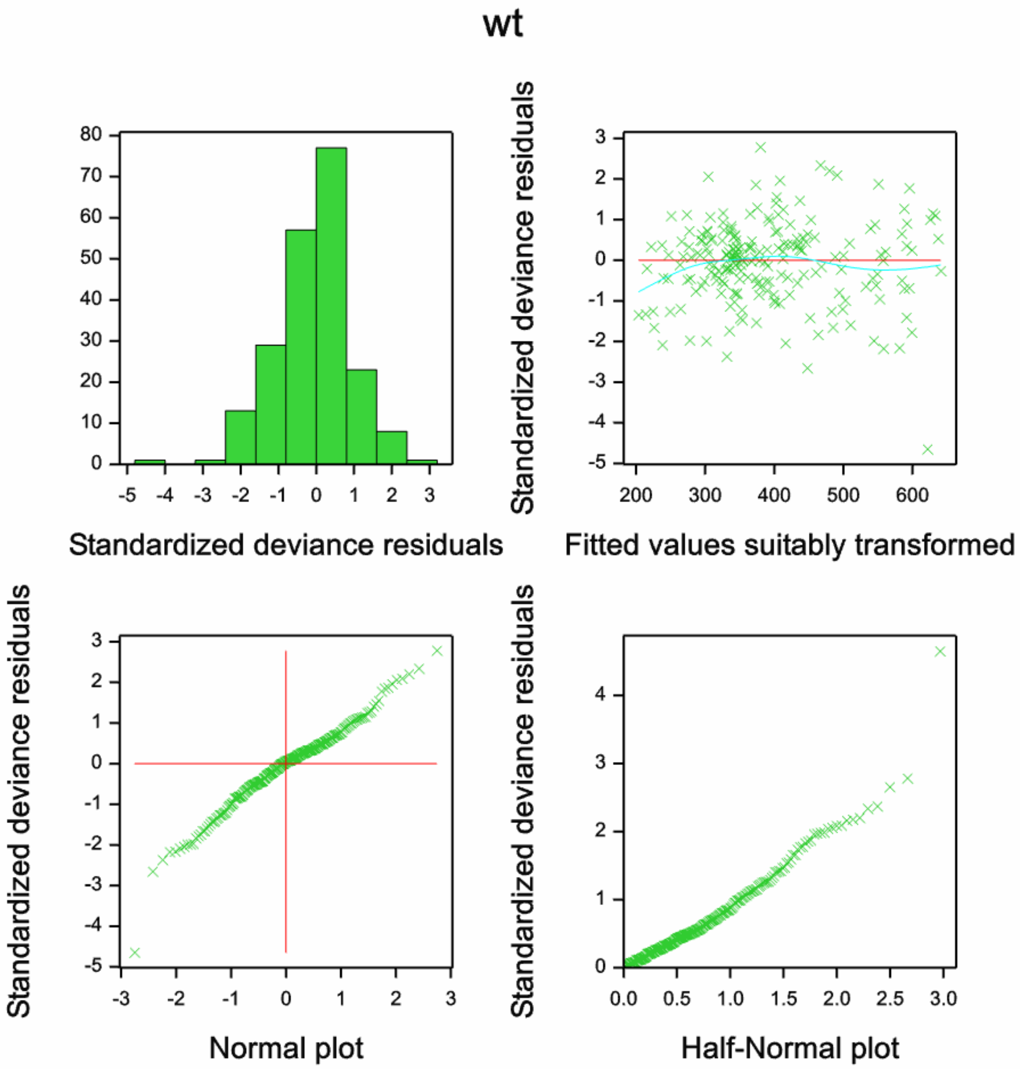


Figure 17-23. Standardised residuals from the Poisson GLM.

17.6.4 Defining target EKP fishing

NSW trawl harvests from 1984 to 2010 were recorded monthly. Each logbook record was a ‘monthly catch return’ for each endorsement holder and vessel. A typical nonzero EKP catch record consisted of 55% EKP, 19% school whiting, 20% octopus, 3% bugs, 3% squid, one degree latitudinal zone of capture and total boat-days fished a month. Given the multi-species complexity of NSW monthly logbook catch and effort, exploratory analyses were used to help define target EKP fishing. A simple logistic regression (binomial distribution and logit link) of ‘month of catch return’ and ‘latitudinal zone’ was used to predict the probability of EKP fishing per catch return. A reasonable EKP monthly catch (or other species) was defined as a catch exceeding the lower quartile of the non-zero catches for that year (Dichmont *et al.* 2001). The results showed no clear discrimination between species based on using the lower quartile rule. For school whiting, a consistent 20%-60% fishing probability remained compared to EKP (Figure 17-24). Based on NSW business rules, a higher 60% catch rule was used to infer EKP catch rates for target fishing. This produced a sensible catch rate scale and minimised the error of incorrectly deflating EKP catchability. Further work is required to improve the definition of NSW target EKP fishing.

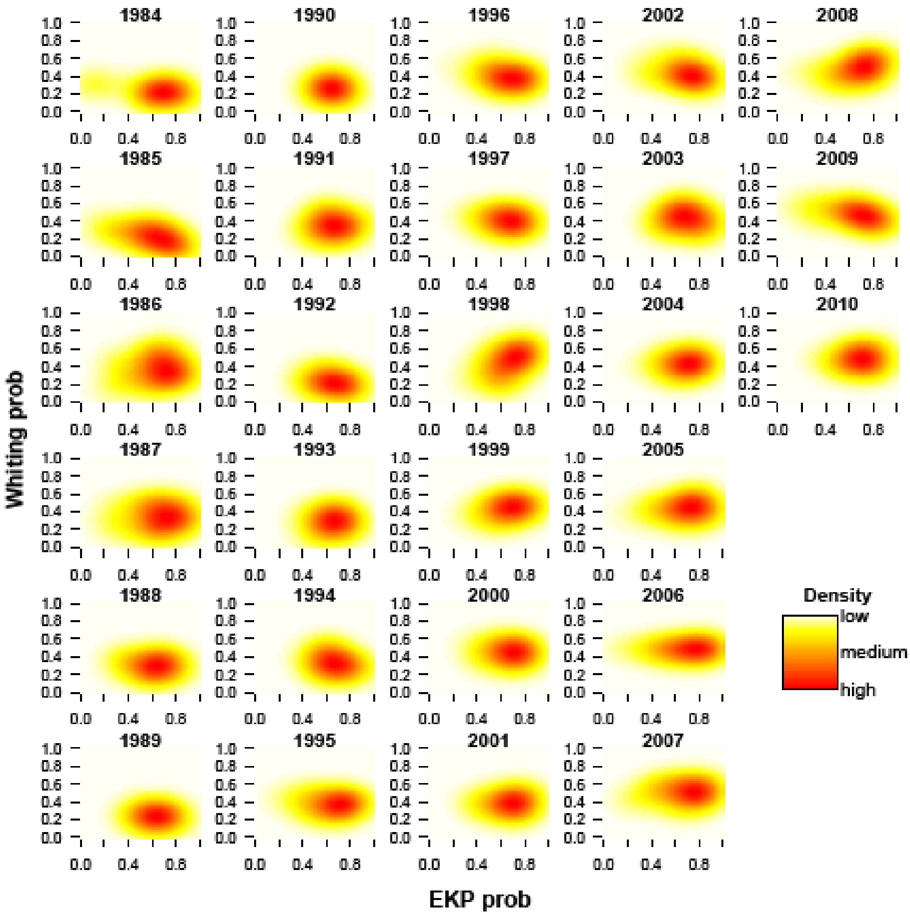


Figure 17-24. Probability of EKP fishing versus school whiting fishing from NSW monthly logbooks by fishing year. The probability plots were for nonzero EKP catches.

For Queensland logbooks, the target EKP and saucer scallop logbook catches were clearly discriminated (Figure 17-25). When the probability of EKP target fishing was high, the saucer scallop probability was low.

It is important to note that for about 90% or more of the Queensland EKP fishery logbook data records the targeted catch is clearly eastern king prawns *M. plebejus* as no other species is reported in the catch. In this respect, the Queensland EKP fishery could almost be described as monospecific, which contrasts strongly with the multispecies nature of the NSW EKP fishery. Only a very minor component of Queensland EKP logbook records are associated with uncertainty in regard to whether the target species is EKP or scallop.

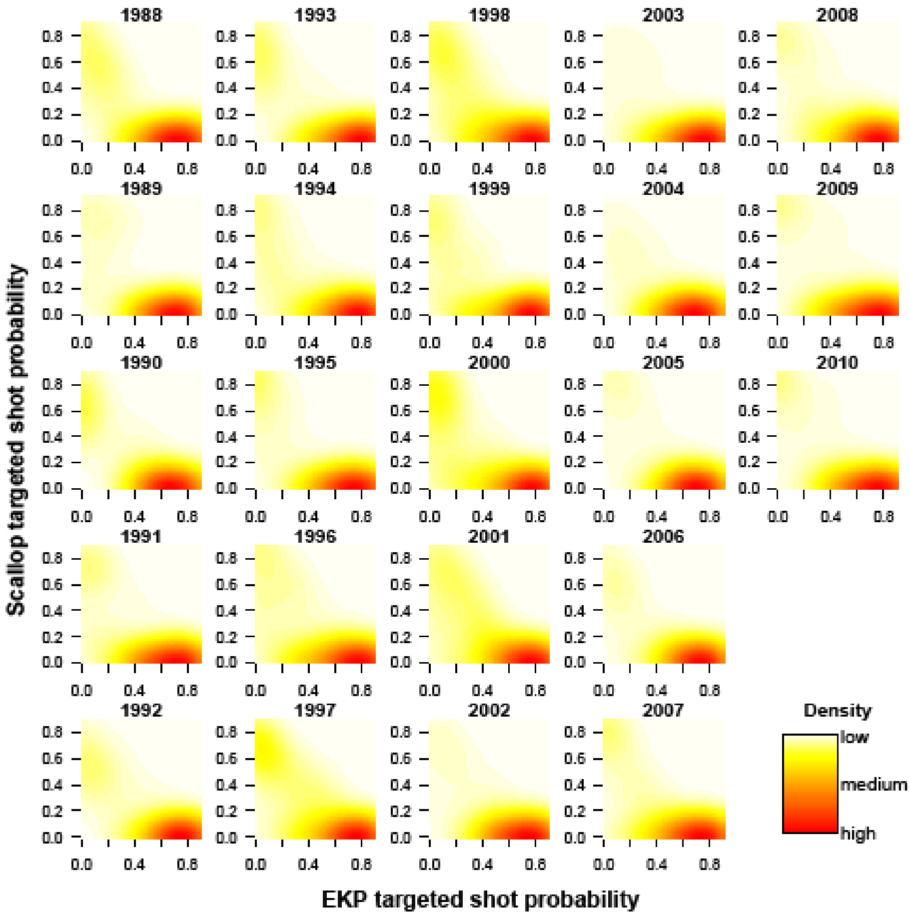


Figure 17-25. Probability of EKP target fishing versus saucer scallop target fishing from Queensland daily logbooks. The probability plots were for nonzero EKP catches.

17.7 SUPPLEMENTARY MATERIAL 2: LENGTH-SPATIAL STRUCTURED MODEL

17.7.1 Calibration and diagnostics

Table 17-14. Parameter estimates and standard errors from the population model fit using a harvest fraction prior of annual catch numbers against recruitment.

	Model: CN_y/R_y prior, $-\log l = -3333.4$, $\sigma_r = 0.115$		
Parameter	Estimate	Standard error	Estimate transformed
ξ	-0.493	0.064	0.379
Υ_1	0.156	0.161	1.169
Υ_2	1.181	0.103	3.258
Υ_3	-2.549	0.259	0.078
Υ_4	1.706	0.092	5.507
μ_1	3.989	0.103	3.989
μ_2	2.329	0.088	2.329
μ_3	-1.006	0.169	-1.006
μ_4	0.183	0.103	0.183
$\kappa_{1 \ldots 3}$	1.697	0.116	1.697
κ_4	0.821	0.080	0.821
l_1^{50}	20.680	0.212	20.680
$l_{2 \ldots 4}^{50}$	24.710	0.156	24.710
$l_{5 \ldots 6}^{50}$	35.541	0.170	35.541
δ	0.914	0.022	0.914
M	0.187	0.008	0.187
ρ	2.695	0.118	0.937

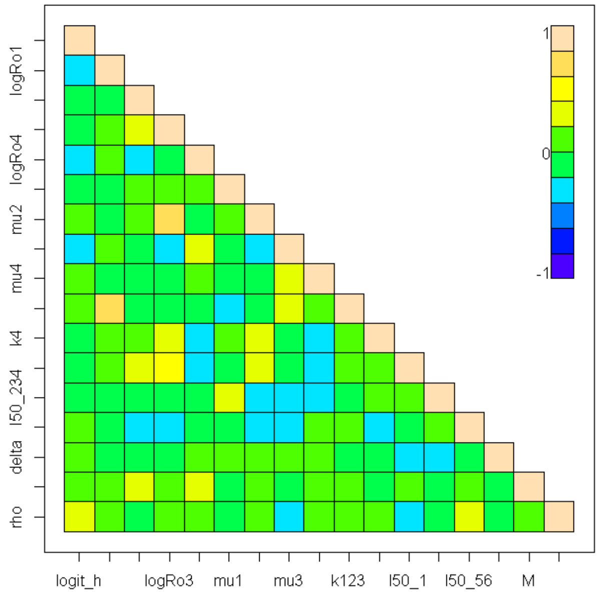


Figure 17-26. Correlation matrix of the 17 leading model parameters. The order of parameter labels correspond to the parameters listed in Table 17-14.

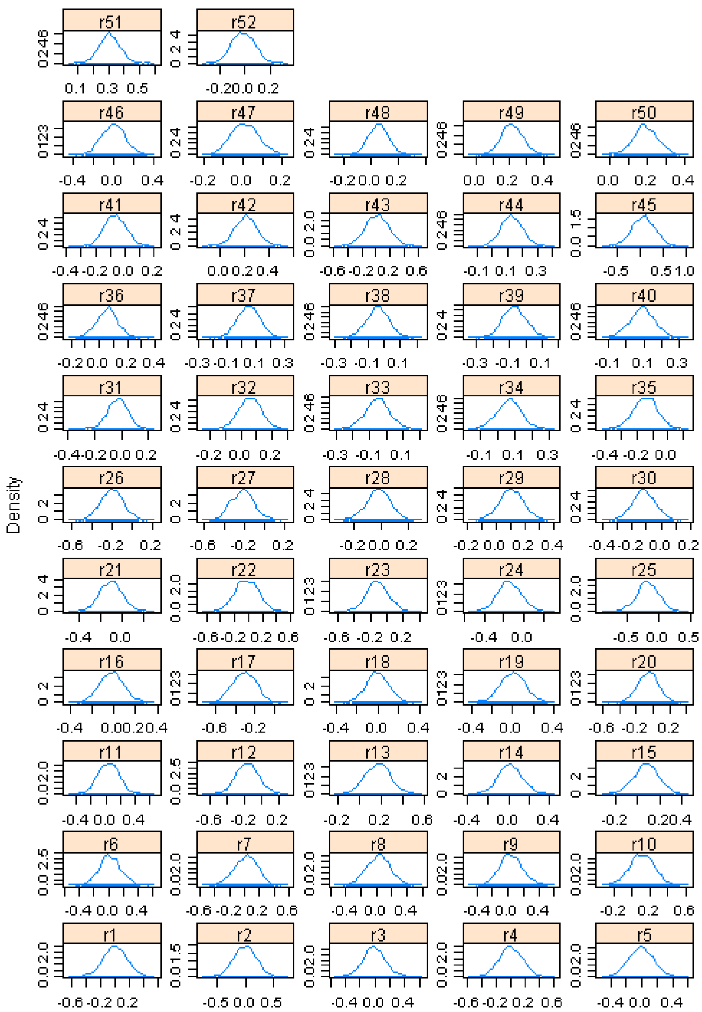


Figure 17-27. Density plots of the 52 recruitment co-ordinate parameters.

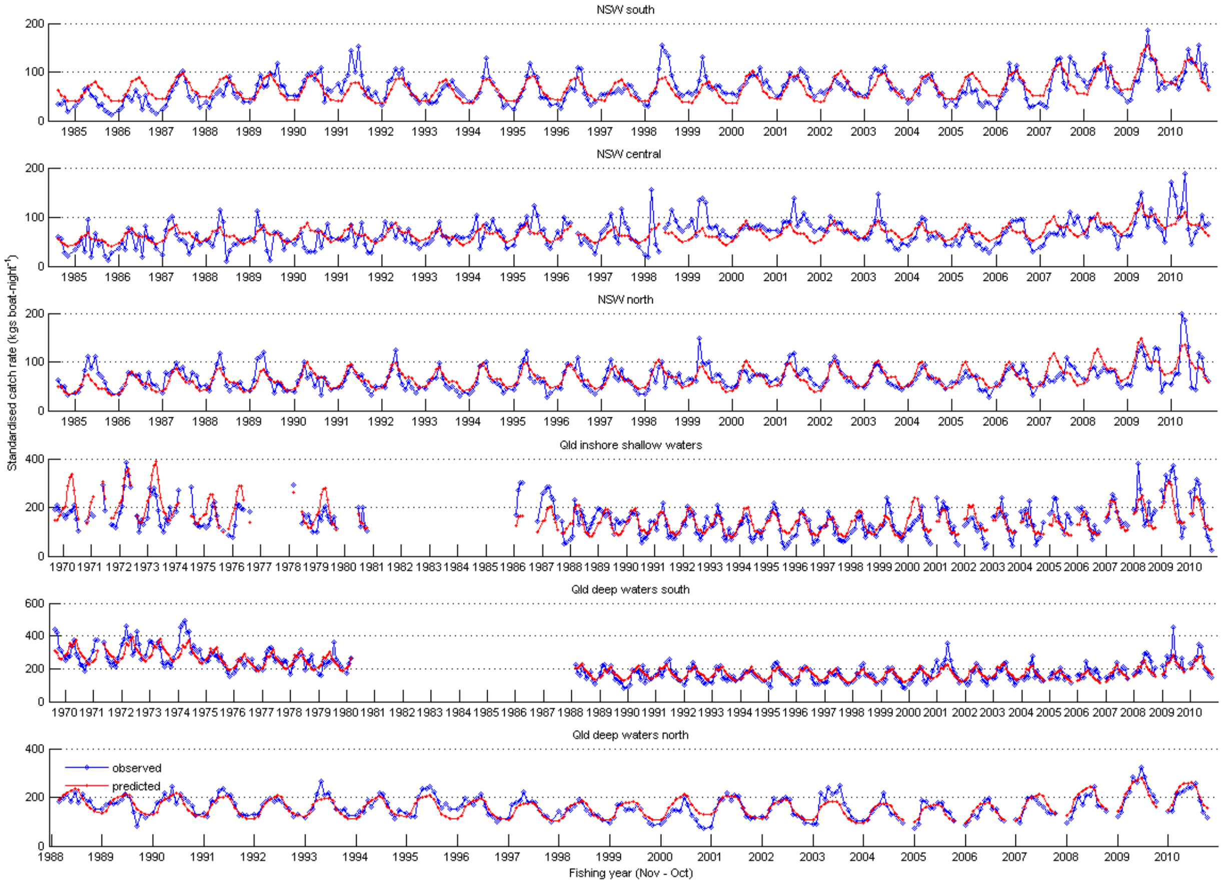


Figure 17-28. Population model predicted fit (red) to the fishery standardised catch rates (blue) for each spatial region 1 (NSW south) to 6 (Qld deep waters north).

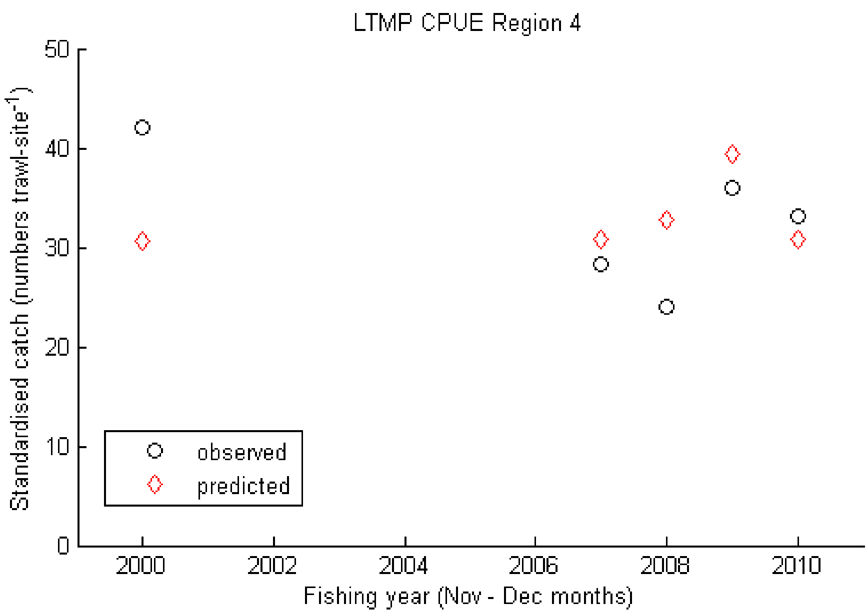


Figure 17-29. Population model predicted fit to the monitoring standardised catch rates for region 4 (Qld inshore shallow waters).

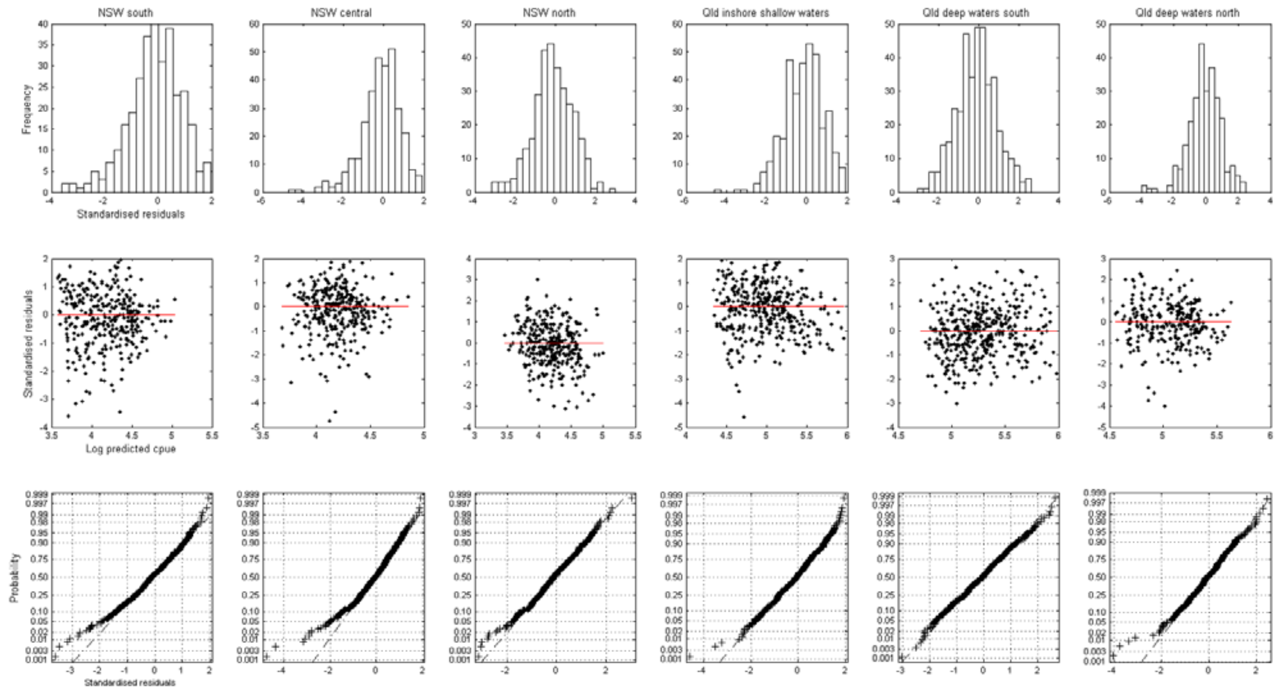


Figure 17-30. Standardised residuals from the population model fit to fishery standardised catch rates for each spatial region 1 (NSW south) to 6 (Qld deep waters north).

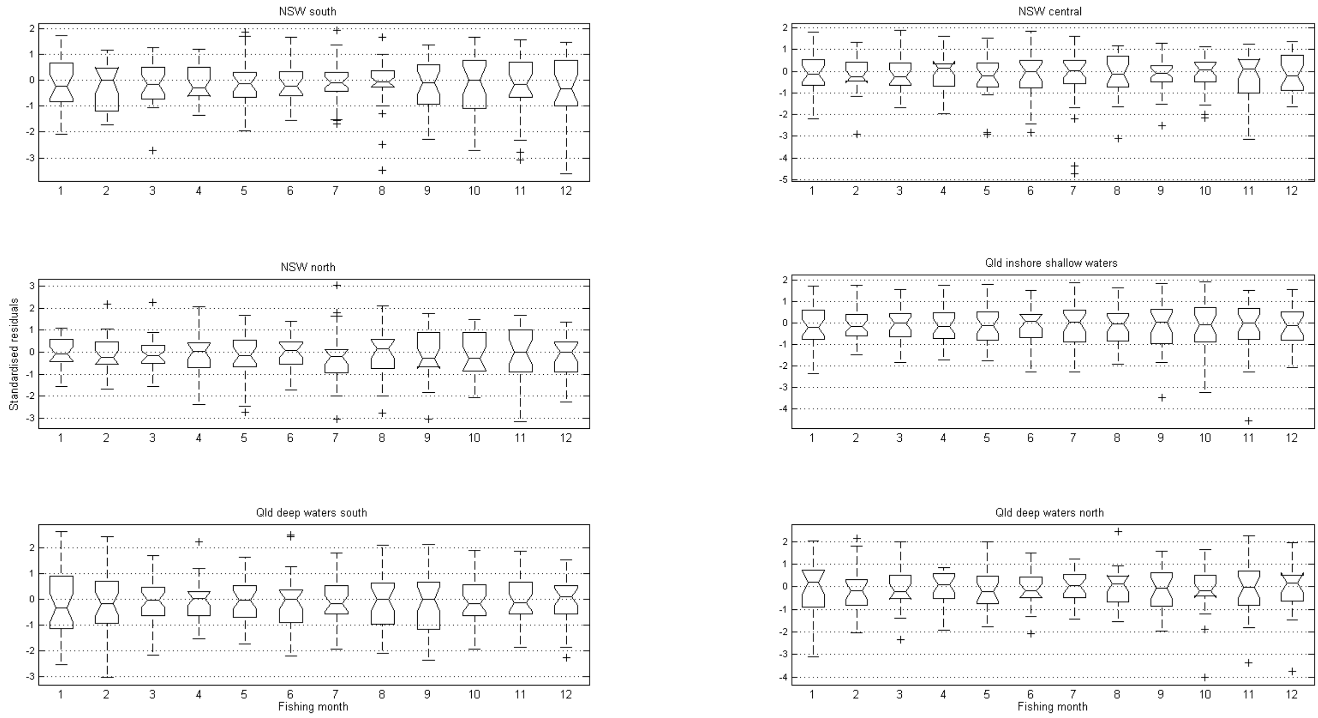


Figure 17-31. Box-plot of standardised residuals by month for each region 1 to 6. The box notches indicate monthly medians were not significantly different from zero at the 5% significance level, with no seasonal trends.

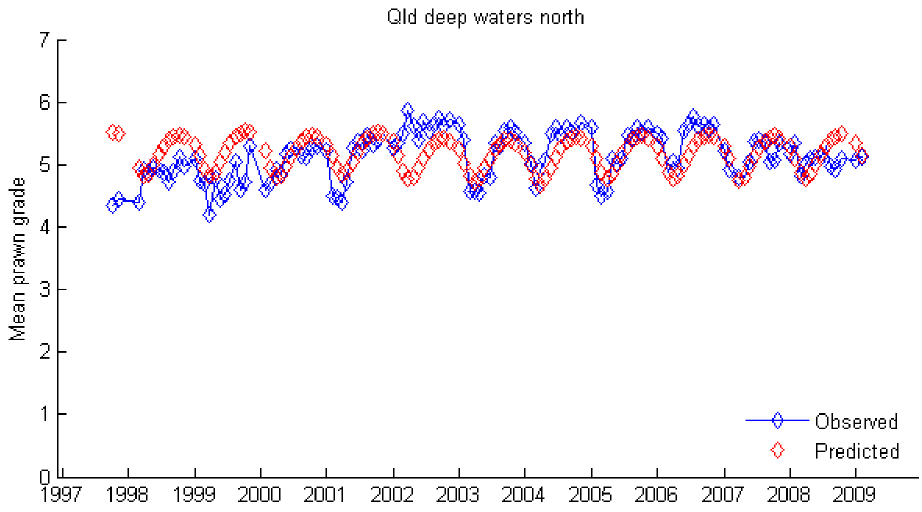


Figure 17-32. Observed and predicted mean catch grades from Queensland deep waters north (region 6).

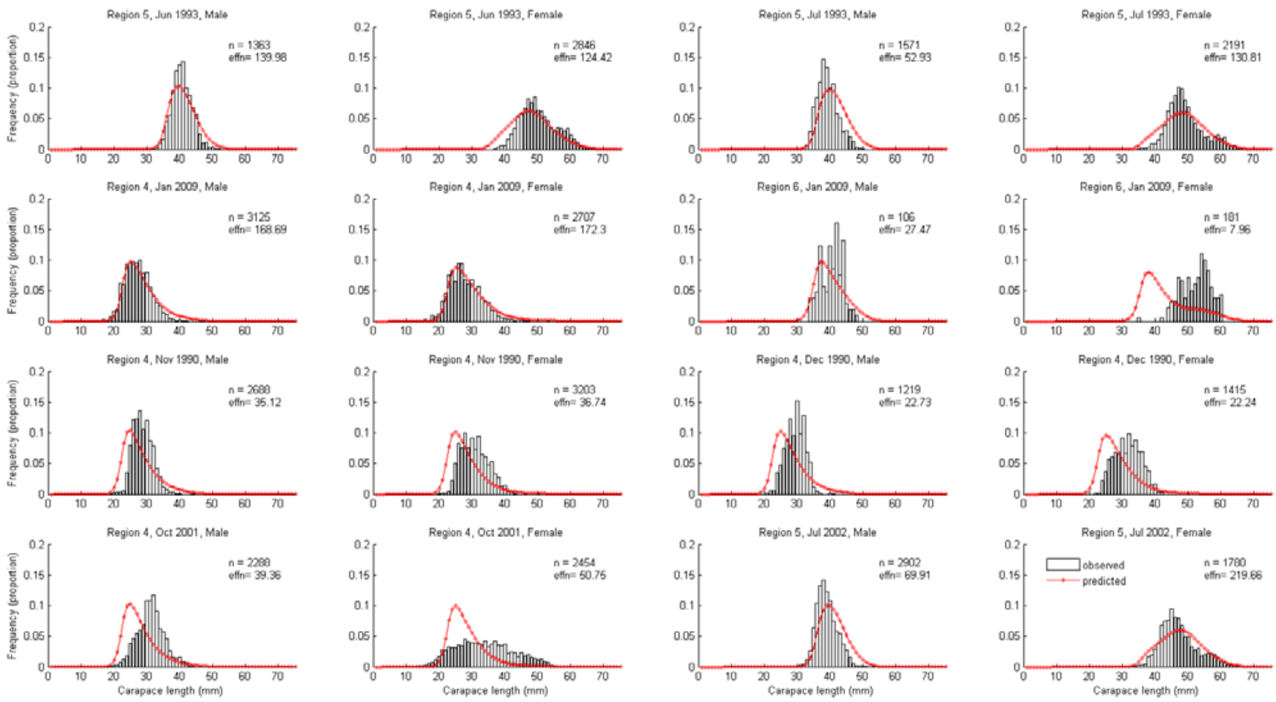


Figure 17-33. Observed and predicted length frequencies (proportions) from Queensland waters (regions 4 to 6); n = number of prawns measured, effn = effective multinomial sample size.

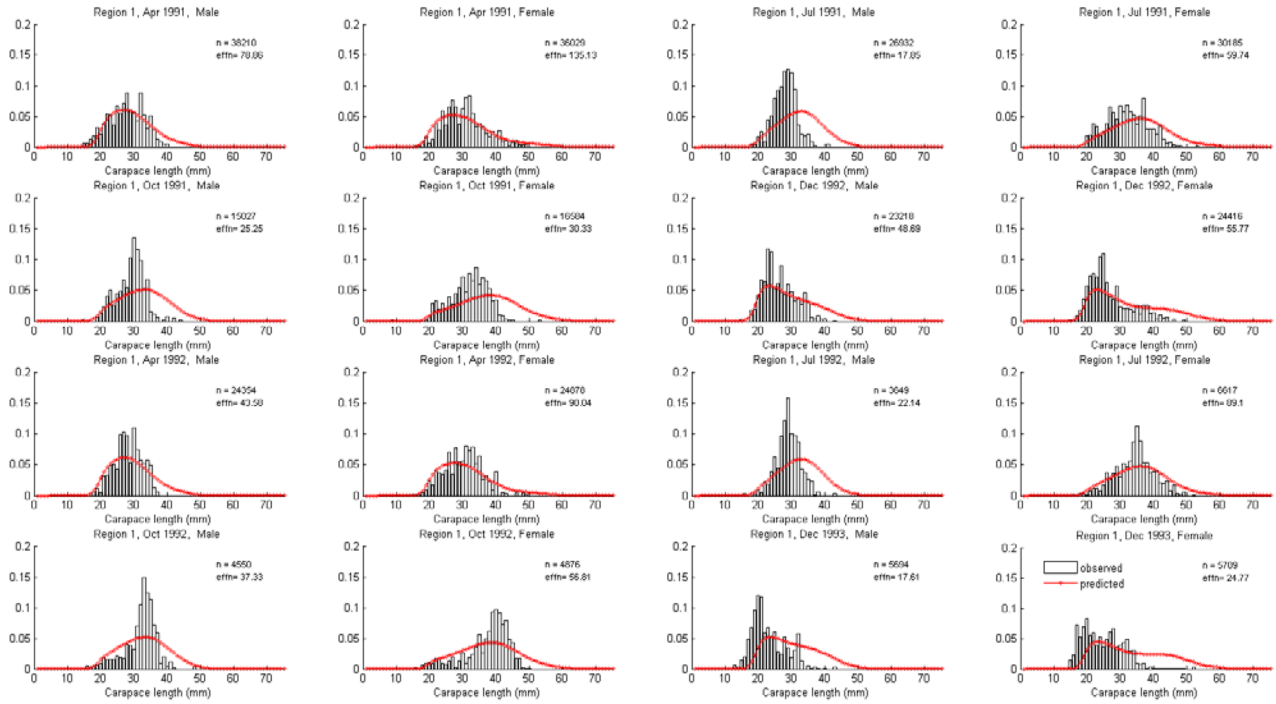


Figure 17-34. Observed and predicted length frequencies (proportions) from region 1 New South Wales waters south; n = number of prawns measured, effn = effective multinomial sample size.

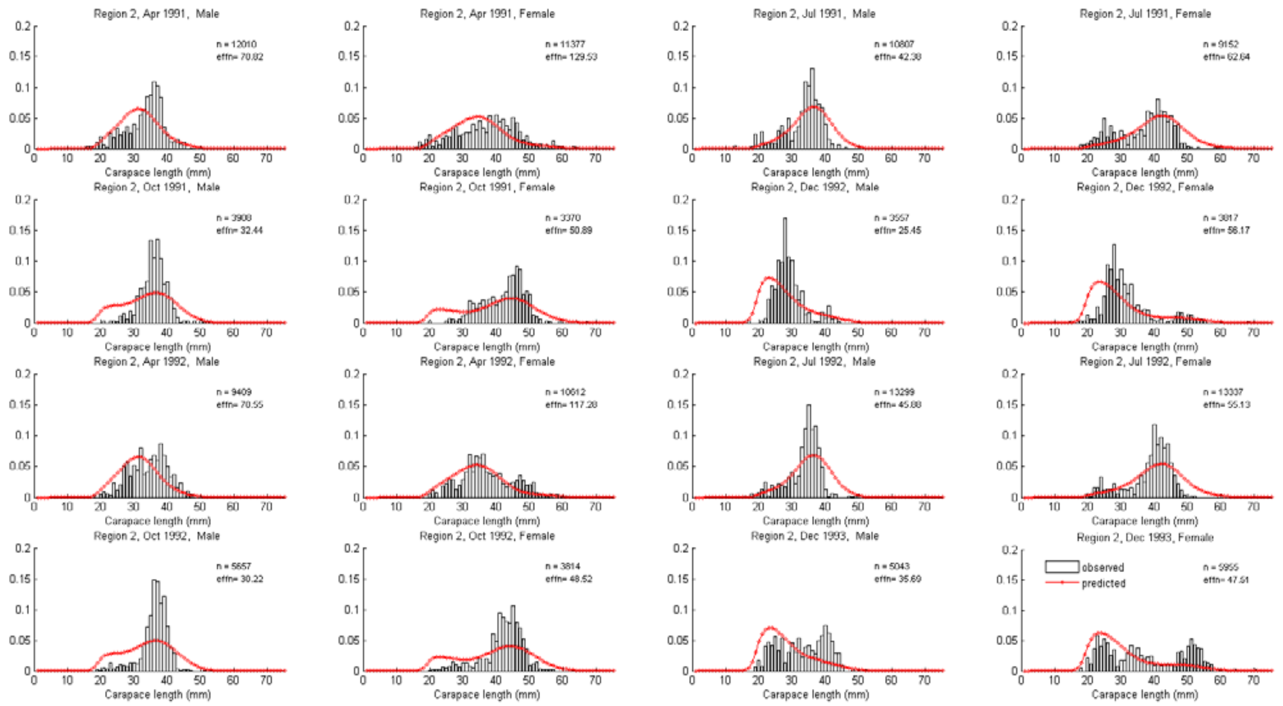


Figure 17-35. Observed and predicted length frequencies (proportions) from region 2 New South Wales central waters; n = number of prawns measured, effn = effective multinomial sample size.

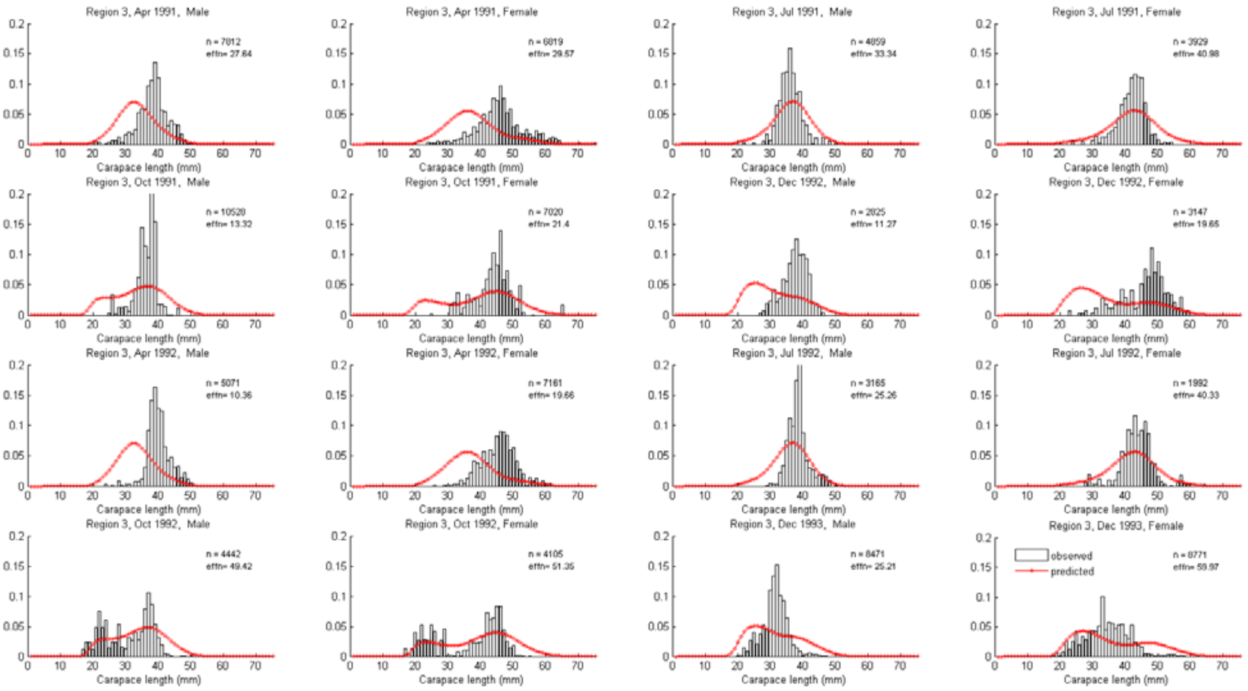


Figure 17-36. Observed and predicted length frequencies (proportions) from region 3 New South Wales waters north; n = number of prawns measured, effn = effective multinomial sample size.

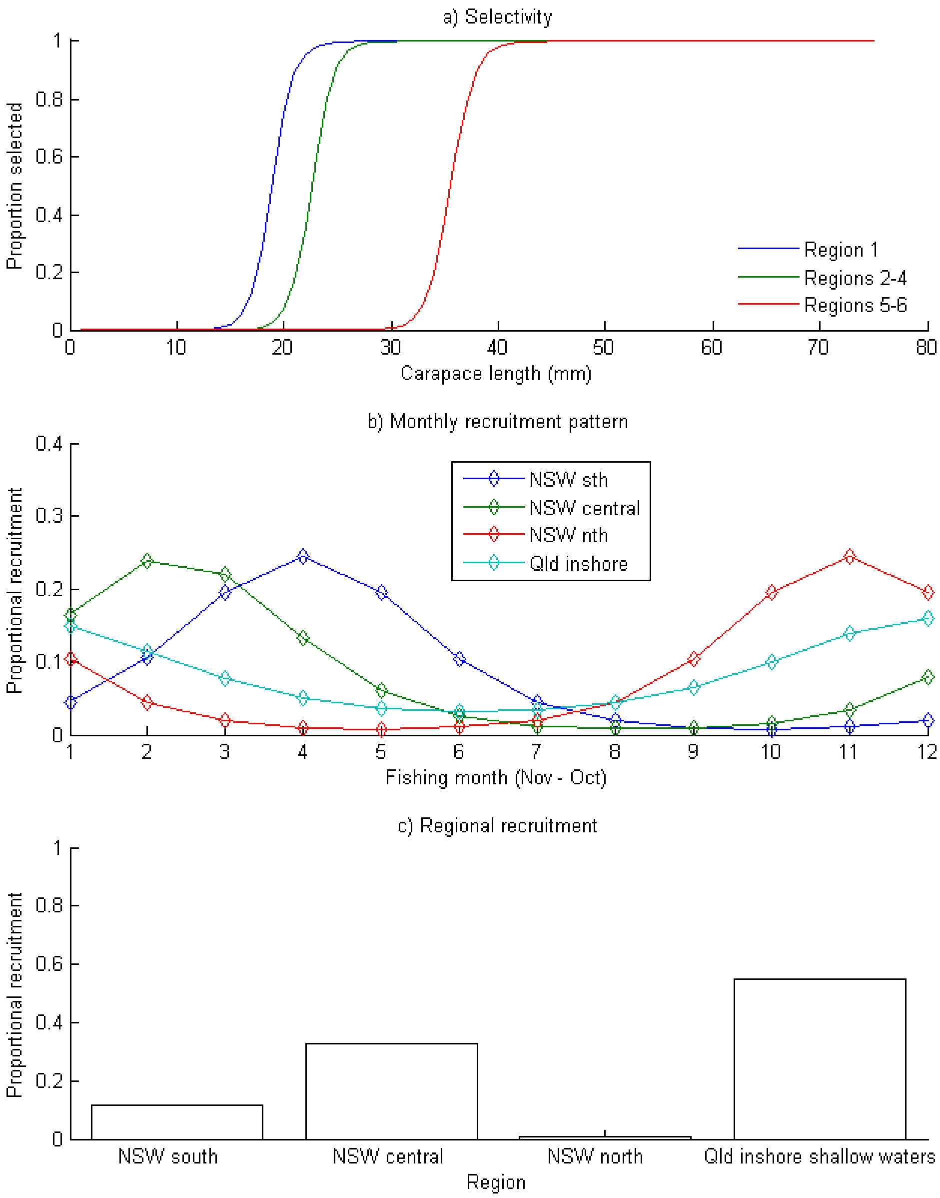


Figure 17-37. Comparison of biological schedules estimated for a) length selectivity, b) monthly recruitment and c) regional recruitment.

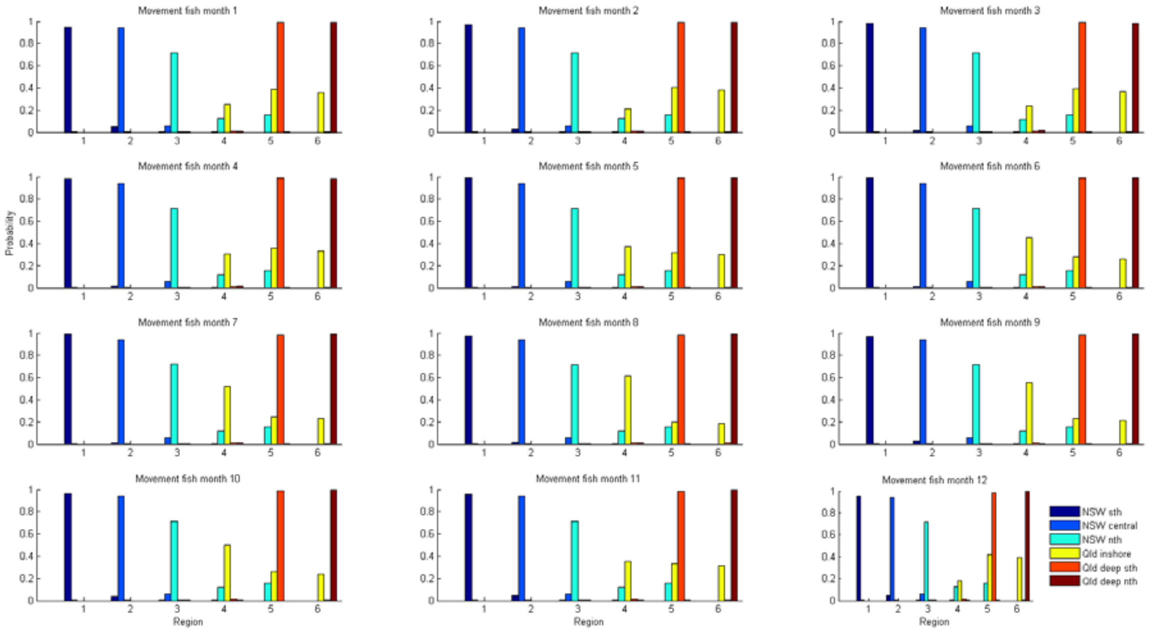


Figure 17-38. Eastern king prawn movement probabilities by fishing months November (1) to October (12). The transition probability from the Queensland inshore shallow waters (region 4) to Queensland deep waters north (region 6) was estimated in stock model. Other movement probabilities were calculated from Braccini *et al.* (2012b) .

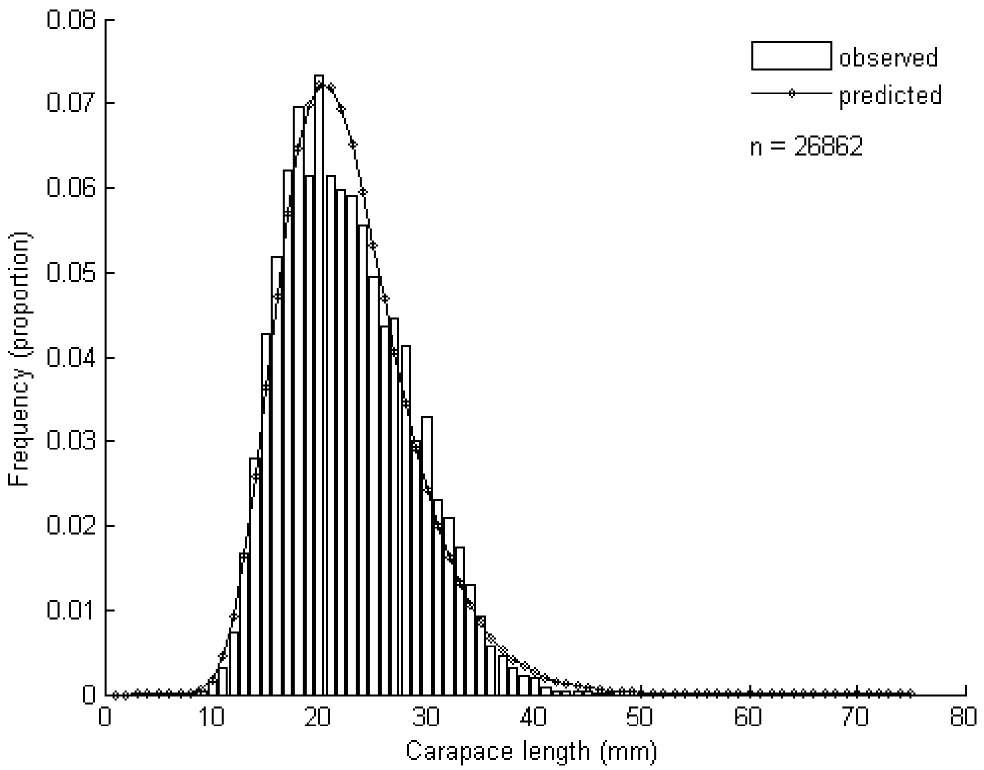


Figure 17-39. Proportion of EKP in each length class at recruitment (Λ = lognormal predicted; n = number of prawns measured in the observed distribution).

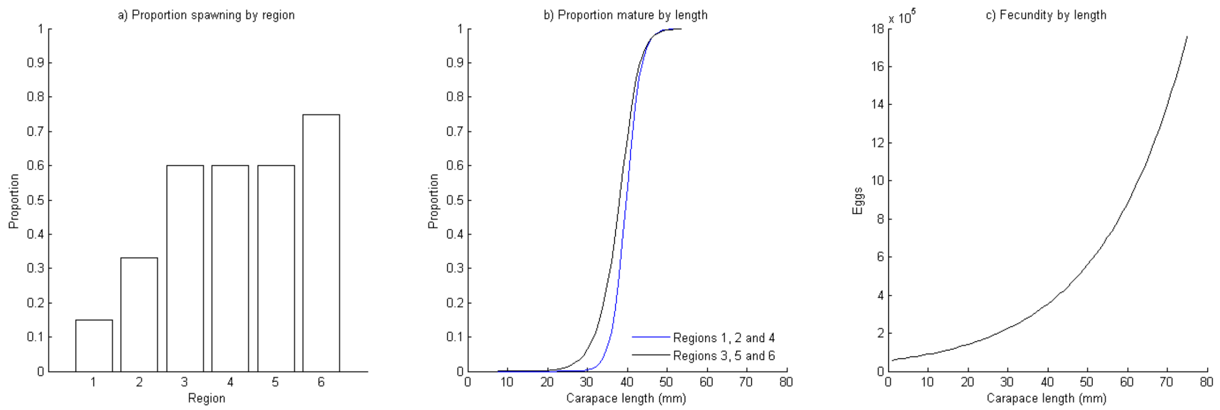


Figure 17-40. EKP spawning, maturity and fecundity schedules by carapace length.

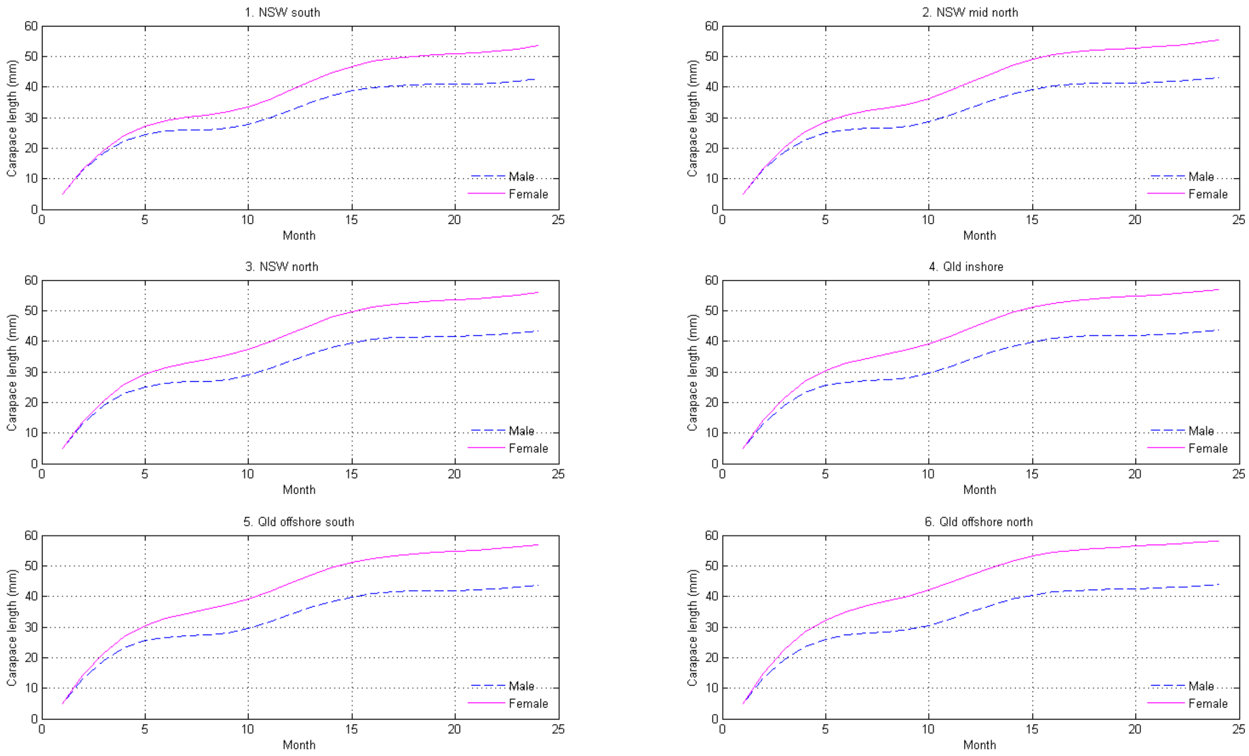


Figure 17-41. EKP growth curves by region and season.

17.7.2 Preliminary MSY and MEY output

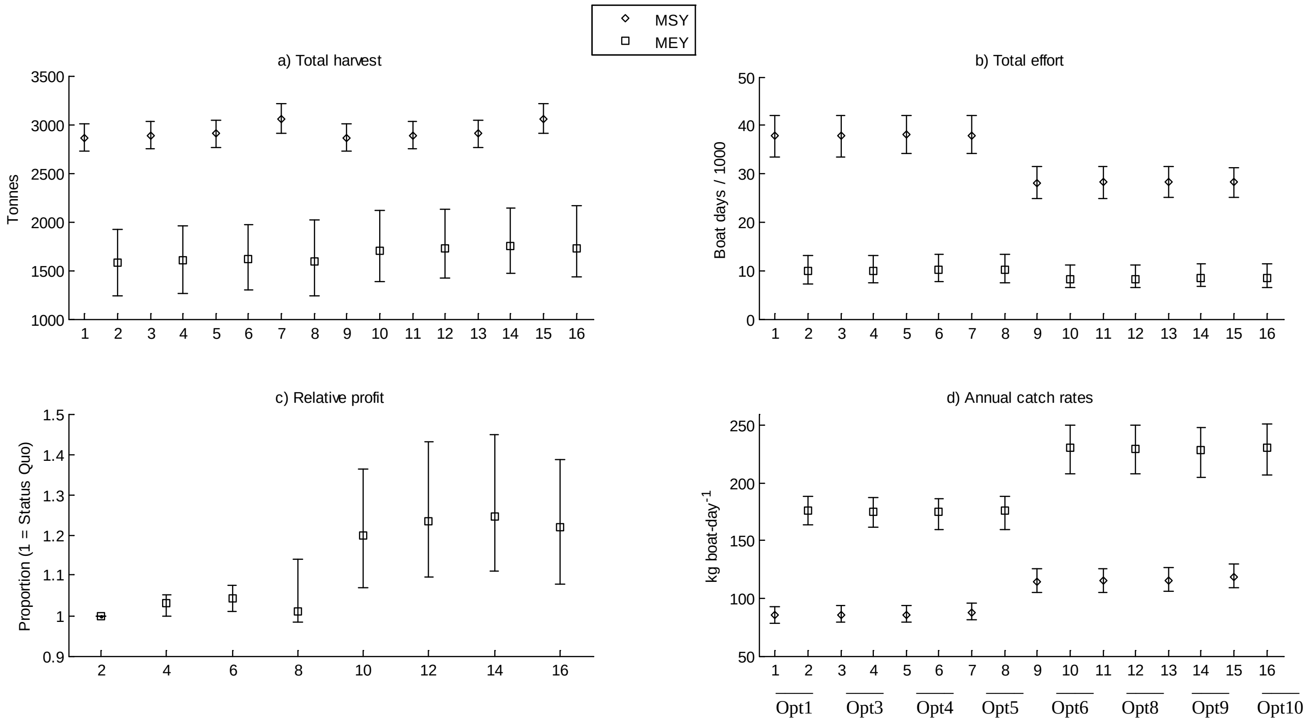


Figure 17-42. Biological and economic reference points for maximum sustainable yield (MSY = diamond symbols) and maximum economic yield (MEY = square symbols), presented at the 24th May 2012 steering committee. Every sequential pair of MSY-MEY corresponded to the optimisations in Table 17-11 (e.g. Opt1 = x-axis 1-MSY and 2-MEY, opt3 = x-axis 3-MSY and 4-MEY, etc.). Note only eight optimisations were run (Opt Nos: 1, 3 to 5, 6, and 8 to 10). Figure subplots show a) annual maximum sustainable and maximum economic yields, b) annual maximum sustainable and maximum economic fishing effort, c) annual maximum relative profit and d) annual catch rates corresponding to maximum sustainable and maximum economic yields/efforts. Error bars represent 95% confidence intervals about their mean. The MEY optimisations assumed the economic values and uncertainties in Table 17-10, and the average number of days fished per boat. This analysis was based on the population model tunned alternatively with a stronger penalty normal log-likelihood for minimum harvest rate.

17.7.3 Supplementary analyses

Analyses were conducted to explore sensitivities in EKP catchability (q_r^{f}) by region. Initially the length-spatial model allowed for different catchability between regions, but with no seasonal pattern (section 17.7.2). This model, like the delay difference model with constant catchability (section 17.8.2), resulted in unwanted seasonal patterns in catch rate residuals. After consideration, the length-spatial model (results in section 17.4) allowed for flexible region x month values of catchability. This produced acceptable catch rate residuals with no seasonal pattern (Figure 17-31). However for region 4 (Qld inshore waters), the flexibility allowed strong change in monthly catchability (Figure 17-43) and marginally early recruitment (mode = November, Figure 17-37; μ_4 Table 17-14). Different catchability equations were therefore examined to constrain the magnitude of change in region 4 catchability. This was to ensure that region 4 model effects were placed appropriately into recruitment, rather than unreasonably into catchability. The supplementary analyses showed that predictive results were equivalent to results in section 17.4 and are described below.

Four sinusoidal functions were considered to model seasonal patterns in catchability (s1…s4; Table 17-15). The functions were based on the variable ‘seqmonth’, denoting sequential months through the population time series. The ‘seqmonth’ was defined so that seqmonth = 12 was close to the peak in catchability ($\propto$ higher water temperature). As the highest average water temperature was in February for all regions, seqmonth was start at 1 in March. This was done to suit the parameterisations, where the expression in brackets may fix the coefficient value of 1 for cos(t). The equations allowed the amplitude (ς) of seasonal variation to vary and the timing of peak catchability was given by parameter ϑ.

Table 17-15. Seasonal catchability equations.

$$q_r^{\mathrm{f}}(t) = \exp\left(\log\left(q_r^{\mathrm{f}}\right) - \varsigma\left(\cos(t) + \vartheta_r \sin(t)\right) \Big/ \sqrt{1+\vartheta_r^2}\right) \qquad \text{(s1)}$$

$$q_r^{\mathrm{f}}(t) = \exp\left(\log\left(q_r^{\mathrm{f}}\right) + \varsigma_r\left(\cos(t) + \vartheta \sin(t)\right)\right) \qquad \text{(s2)}$$

$$q_r^{\mathrm{f}}(t) = \exp\left(\log\left(q_r^{\mathrm{f}}\right) + \varsigma\left(\cos(t) + \vartheta \sin(t) + \omega\cos(2t) + \psi \sin(2t)\right)\right) \qquad \text{(s3)}$$

$$q_r^{\mathrm{f}}(t) = \exp\left(\log\left(q_r^{\mathrm{f}}\right) + \varsigma_r\left(\cos(t - \vartheta_r)\right)\right) \qquad \text{(s4)}$$

$$t = 2\pi \,\mathrm{seqmonth}/12$$

For EKP, equation s1 provided balance to control the magnitude of catchability across regions. The function had single fixed amplitude and allowed different regional peaks. Equation s1 was divided by a square root term to ensure the parameters were not periodic. In comparing catchability results (region x month – Figure 17-43 against s1 – Figure 17-44.), NSW and Qld deep waters had similar estimates. Region 4 estimates were reduced but with similar monthly pattern. The regional amplitude was estimated at 20% and the region 4 recruitment mode was in December (Table 17-16). Other parameter estimates were similar comparing Table 17-14 and Table 17-16, except the movement fraction ρ was less at 0.71. The residuals were adequate, but some minor and unexplained seasonal error remained (Figure 17-45). The MSY and MEY values were similar comparing Figure 17-46 ($\bar{d}$), Figure 17-47 ($2\bar{d}$) and Figure 17-48 (variable costs only) against results in section 17.4.2; further description provided there. The monthly pattern in MSY and MEY catch rate reference points were more smoothed (Figure 17-49).

Equation s2 was similar in structure to s1, but allowed the amplitude of seasonal variation to vary between regions with fixed peak. This function resulted in strong amplitude for region 4 (similar to region 4 in Figure 17-43).

Equation s3 fixed the same seasonal variation (peak and amplitude) across regions and the parameters ω and ψ allowed uneven pattern. The fixed catchability pattern produced a lesser model fit ($-\log l = -3211.7$) with seasonal patterns in catch rate residuals still present.

Equation s4 allows full regional variation through different regional peaks and amplitudes. It was not applied as the function would produce similar results to Figure 17-43, with strong amplitude for region 4. Equation s4 was listed to describe the range of functions considered.

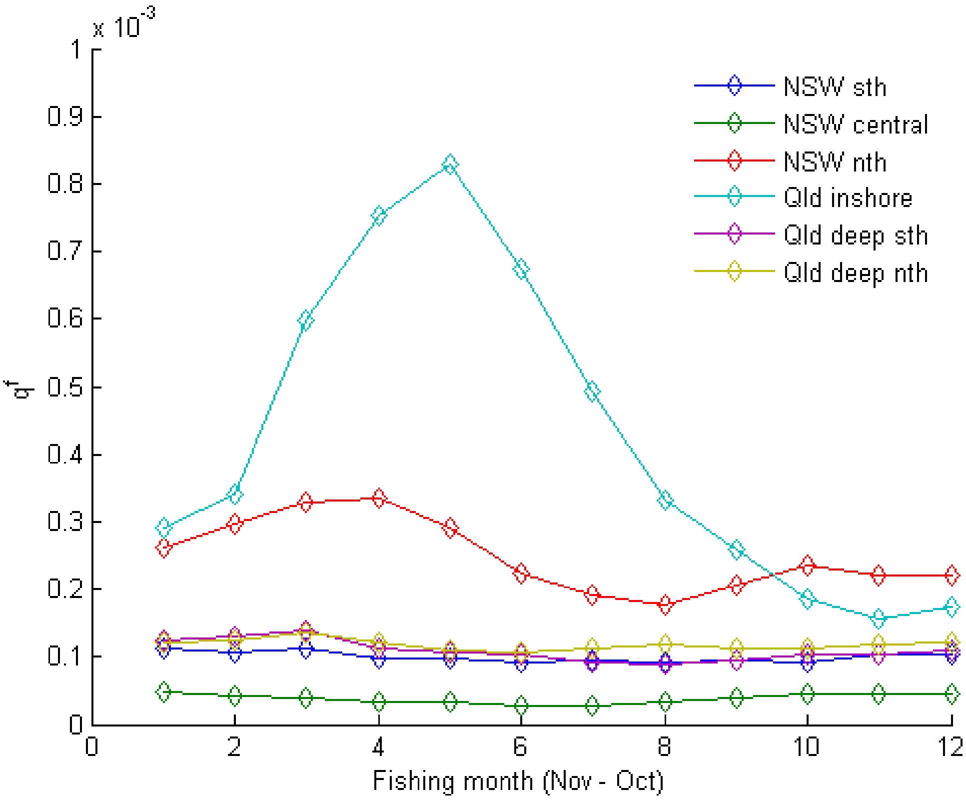


Figure 17-43. Fishery catchability by month and region.

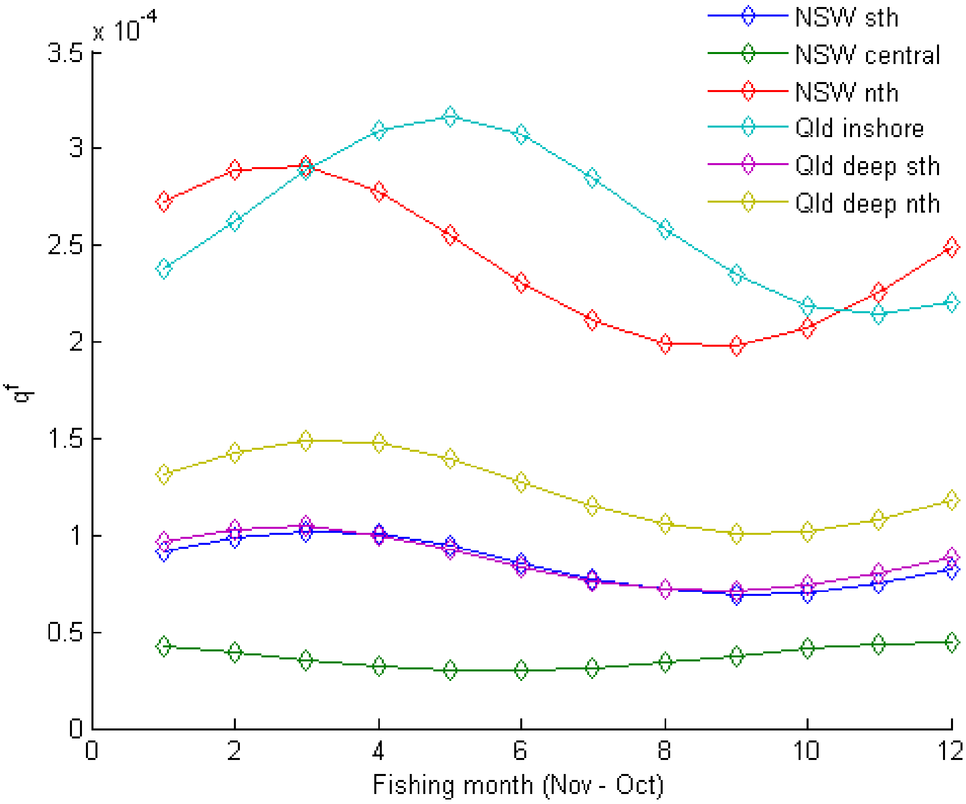


Figure 17-44. Fishery catchability from function s1 (Table 17-15).

Table 17-16. Parameter estimates and standard errors from the population model fit using catchability function s1.

	Model: CN_y / R_y prior, $-\log l = -3253.7$ $\sigma_r = 0.115$		
Parameter	Estimate	Standard error	Estimate transformed
ξ	-0.568	0.089	0.362
Υ_1	0.289	0.206	1.335
Υ_2	1.171	0.103	3.225
Υ_3	-2.713	0.48	0.066
Υ_4	1.772	0.083	5.884
μ_1	4.361	0.141	4.361
μ_2	1.918	0.153	1.918
μ_3	-1.165	0.259	-1.165
μ_4	1.949	0.112	1.949
$\kappa_{1\ldots3}$	1.573	0.132	1.573
κ_4	0.819	0.071	0.819
l_1^{50}	20.671	0.661	20.671
$l_{2\ldots4}^{50}$	24.483	0.731	24.483
$l_{5\ldots6}^{50}$	35.551	0.193	35.551
δ	0.921	0.027	0.921
M	0.184	0.005	0.184
ρ	0.939	0.281	0.719
ς	0.196	0.012	0.196
ϑ_1	-0.455	0.279	-0.455
ϑ_2	1.261	0.236	1.261
ϑ_3	-0.876	0.273	-0.876
ϑ_4	0.521	0.307	0.521
ϑ_5	-0.800	0.137	-0.800
ϑ_6	-0.356	0.179	-0.356

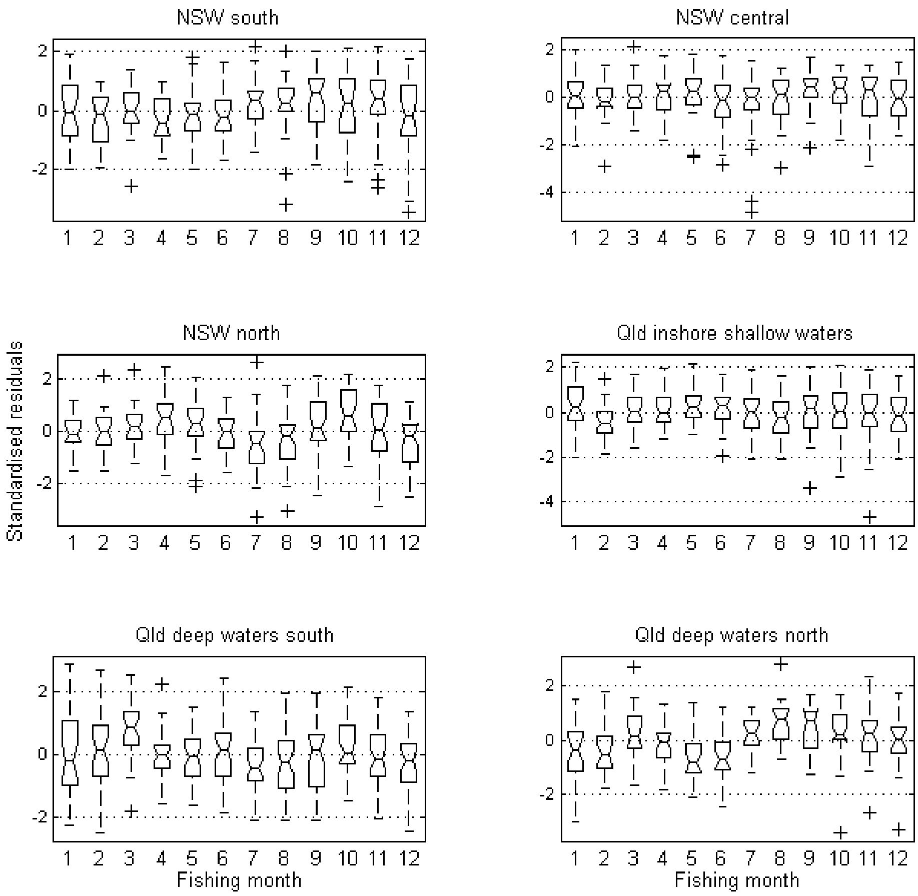


Figure 17-45. Box-plot of standardised residuals using catchability function s1 (Table 17-15) by month for each region 1 to 6.

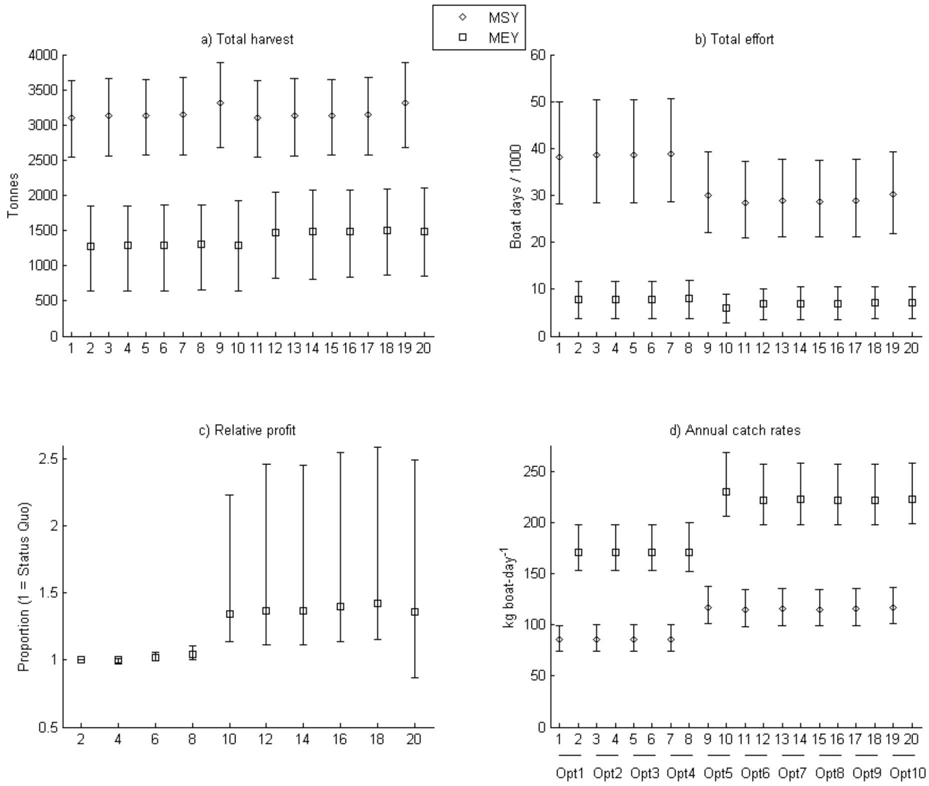


Figure 17-46. Maximum sustainable yield (MSY = diamond symbols) and maximum economic yield (MEY = square symbols) reference points for Australia's east coast EKP (NSW and Qld waters) using catchability function s1. Every sequential pair of MSY-MEY corresponded to the optimisations in Table 17-11 (e.g. Opt 1 = x-axis 1-MSY and 2-MEY, Opt 2 = x-axis 3-MSY and 4-MEY, etc.). Figure subplots show a) annual maximum sustainable and maximum economic yields, b) annual maximum sustainable and maximum economic fishing effort, c) annual maximum profit relative to Opt 1, and d) annual catch rates corresponding to maximum sustainable and maximum economic yields/efforts. Error bars represent 95% confidence intervals about their mean. The MEY optimisations assumed the economic values and uncertainties in Table 17-10, and the average number of days fished per boat ($\overline{d}$).

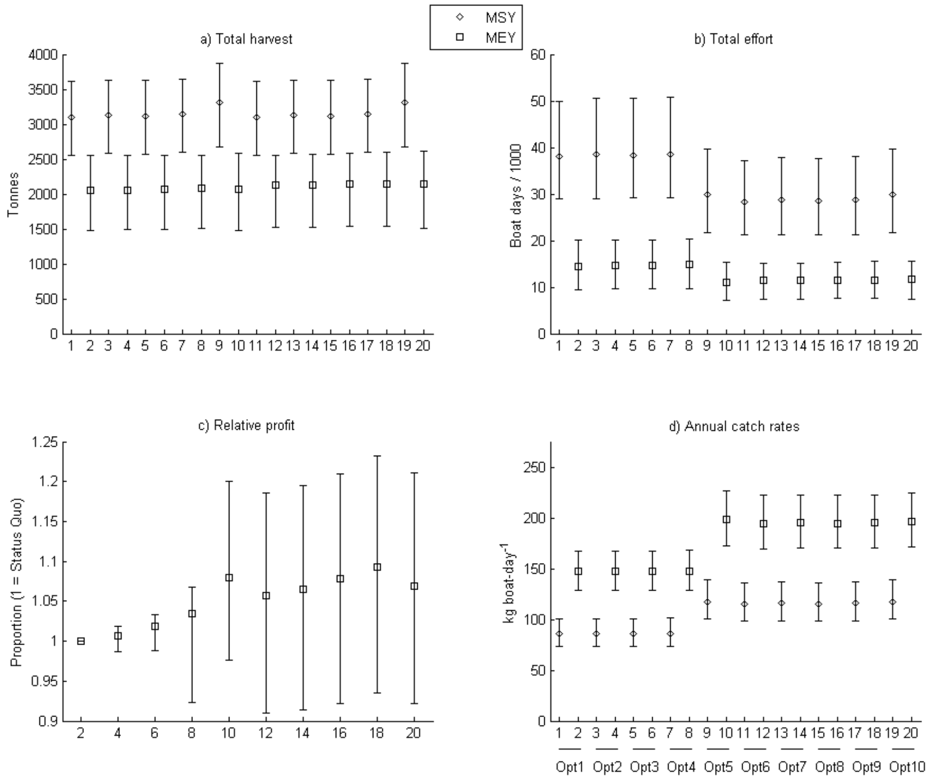


Figure 17-47. Maximum sustainable yield (MSY = diamond symbols) and maximum economic yield (MEY = square symbols) reference points for Australia's east coast EKP (NSW and Qld waters) using catchability function s1. Every sequential pair of MSY-MEY corresponded to the optimisations in Table 17-11 (e.g. Opt 1 = x-axis 1-MSY and 2-MEY, Opt 2 = x-axis 3-MSY and 4-MEY, etc.). Figure subplots show a) annual maximum sustainable and maximum economic yields, b) annual maximum sustainable and maximum economic fishing effort, c) annual maximum profit relative to Opt 1, and d) annual catch rates corresponding to maximum sustainable and maximum economic yields/efforts. Error bars represent 95% confidence intervals about their mean. The MEY optimisations assumed the economic values and uncertainties in Table 17-10, but twice the average number of days fished per boat ($2\bar{d}$).

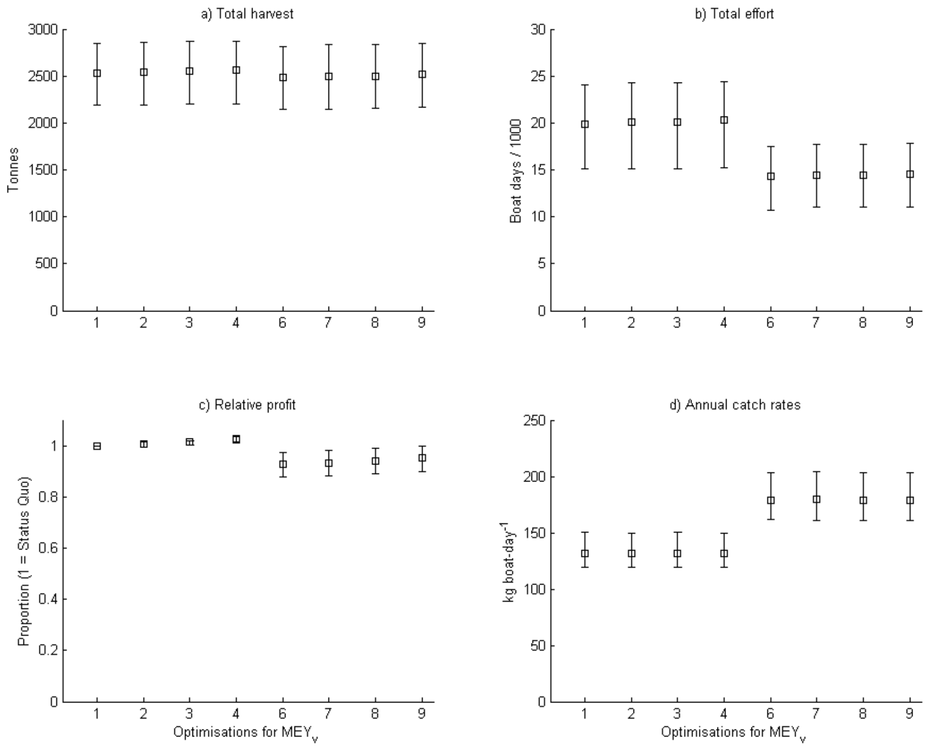


Figure 17-48. Maximum economic yields for Australia's east coast EKP (NSW and Qld waters) under variable costs only (MEY_v) using catchability function s1. Every sequential MEY_v corresponded to the optimisations in Table 17-11 (Opt1 to Opt 4 and Opt 6 to Opt 9). Figure subplots show a) maximum economic yields$_v$, b) annual maximum economic fishing effort$_v$, c) annual maximum profit$_v$ relative to Opt 1, and d) annual catch rates corresponding to maximum economic yields$_v$ and efforts$_v$. Error bars represent 95% confidence intervals about their mean. The MEY_v optimisations assumed the economic values and uncertainties in Table 17-10, and fixed costs were excluded.

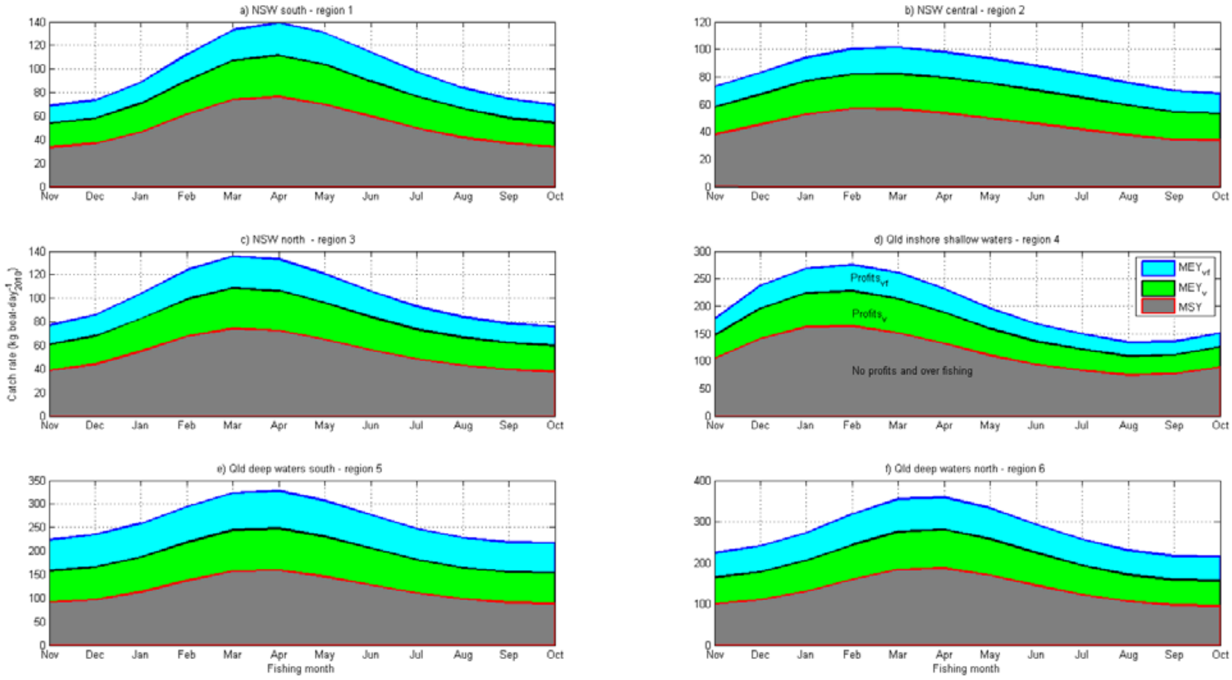


Figure 17-49. Average monthly catch rate targets for maximum sustainable yield (MSY), maximum economic yield for variable costs (MEY_v), and MEY_{vf} for variable costs plus fixed costs by fishing region using catchability function s1.

17.8 SUPPLEMENTARY MATERIAL 3: DELAY DIFFERENCE MODEL

17.8.1 Whole-fishery catch rate data

The whole-of-fishery monthly catch rates of eastern king prawns from 1969 to 2010 (Figure 17-50) was derived from the six regional standardised indices (Figure 17-28). Missing regional averages between 1969 and 1981 for regions 1, 2, 3 and 6 were predicted using a GLM accounting additively for the effects of time (fishing year * month) and regions. The imputation of missing regional catch rates was preferred over discarding these fishing months altogether (Walters 2003). The six regional time series were combined into a whole-of-fishery average weighted by the relative size of the fished area in each region (Table 17-17.); as suggested by Campbell (2004) and Carruthers *et al.* (2011). In this case, the whole-of-fishery weighted average was found to be equivalent to GenStat's GLM predictions where region was standardised according to the number of occurrences of each of its levels in the whole dataset (marginal weights policy; Figure 17-51). Other modifications to the weights of Table 17-17 also resulted in similar averages.

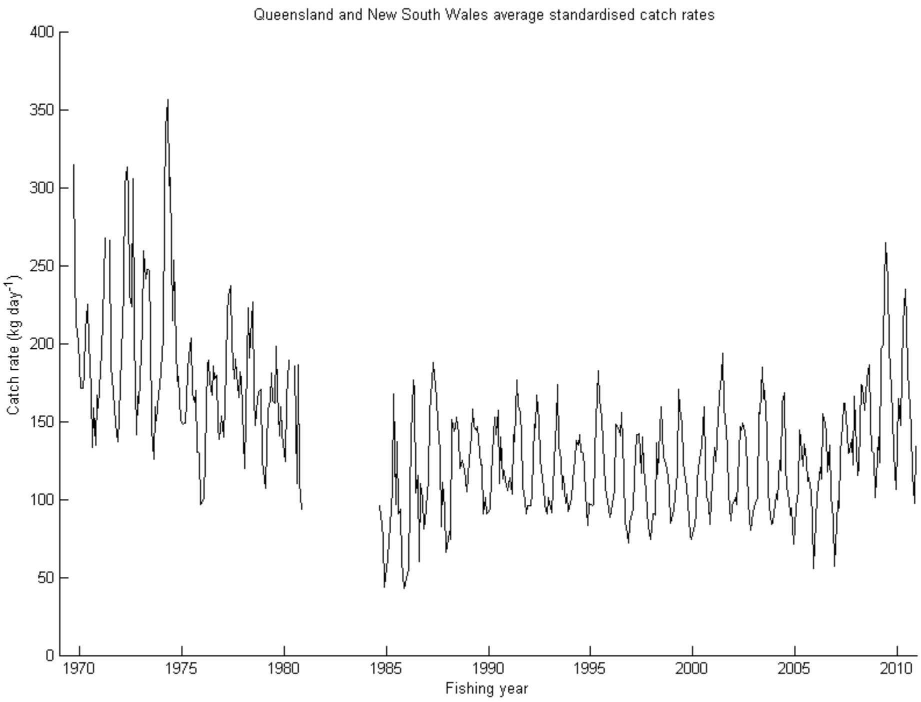


Figure 17-50. Whole-of-fishery monthly standardised catch rates.

Table 17-17. Relative effective area fished for eastern king prawns in each region along the east coast of Australia.

Region	Area
1. NSW south	0.14
2. NSW central	0.11
3. NSW north	0.11
4. Qld inshore shallow waters	0.17
5. Qld deep waters south	0.19
6. Qld deep waters north	0.28

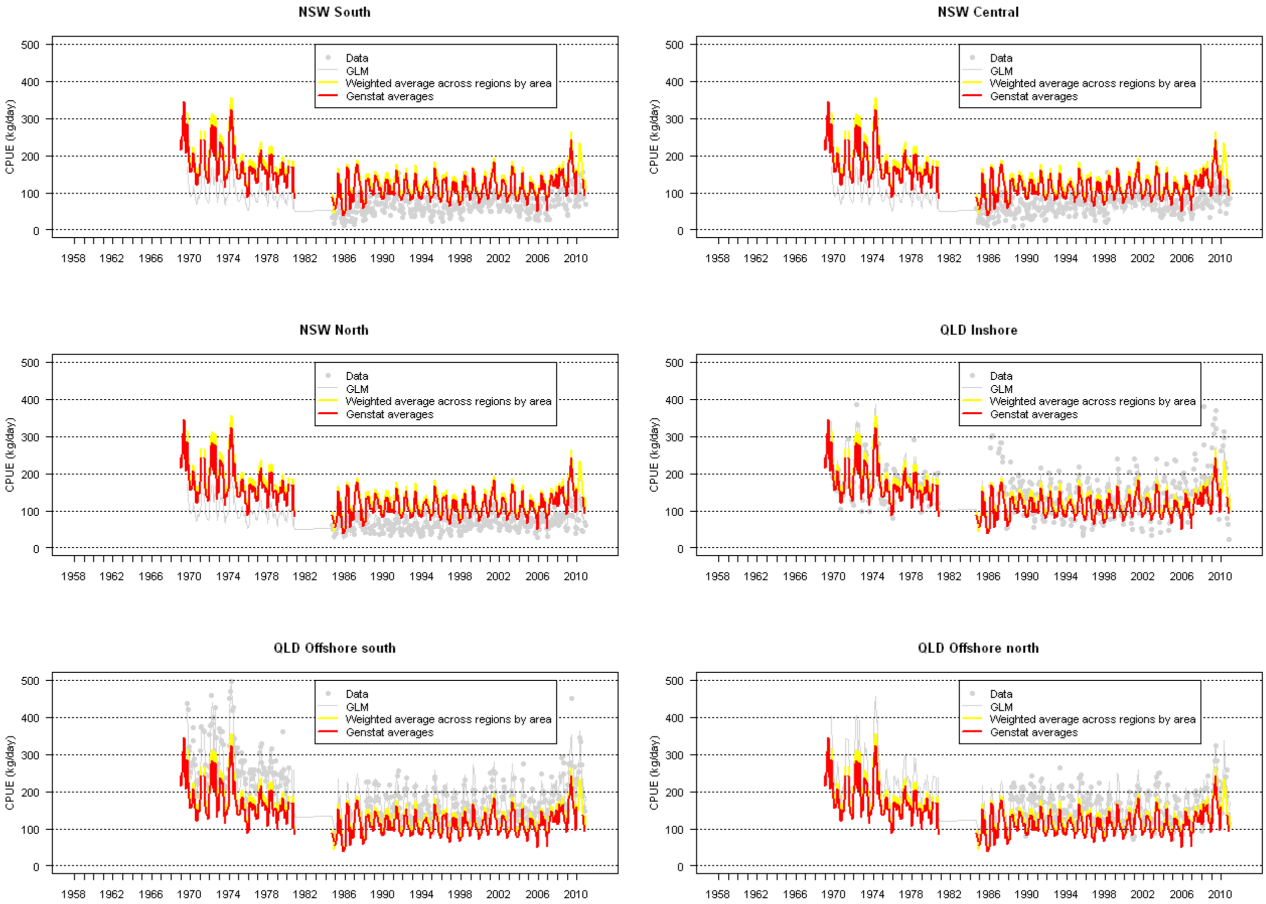


Figure 17-51. Comparison of whole-of-fishery standardised catch rates for the area-weighted and Genstat marginal-weighted methods against each regions data and imputed GLM data.

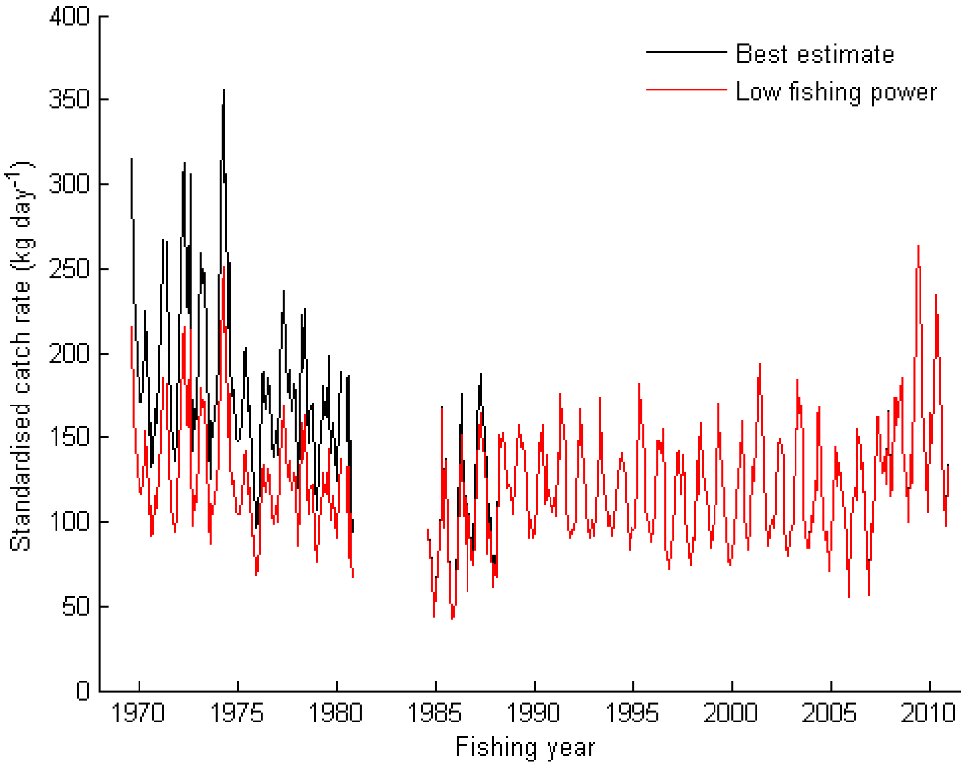


Figure 17-52. Whole-of-fishery monthly standardised catch rates (best estimate) compared against lower fishing power prior to 1988.

17.8.2 Calibration, diagnostics and estimates

The delay difference model tracked the trend in standardised catch rates quite well (Figure 17-53). The between-year variations were generally captured and the diagnostic plots do not indicate any lack of fit (Figure 17-54). The use of log-normal errors was appropriate with no overall pattern in standardised residuals and linear normality plots. A within-year pattern of standardised residuals was present where the model marginally underestimated the monthly peak catch rates and overestimated the monthly catch rates minima (Figure 17-53). This was due to the expectation of logarithm recruitment deviates having a mean of zero between 1958 and 2010 (see log-likelihood functions in section 17.3.1), and assuming constant catchability q. The residual zero-expectation was required to estimate uncertainty in recruitment over 53 years, especially for early years when catch rate data were not present. Constant catchability was maintained to provide contrast against the length-spatial structure model which included monthly variation in catchability. Model fits to recruitment survey catch rates were uninformative (Figure 17-55). Model fits to catch rates and standardised residuals were similar for model 2, sensitivity 1 and sensitivity 2.

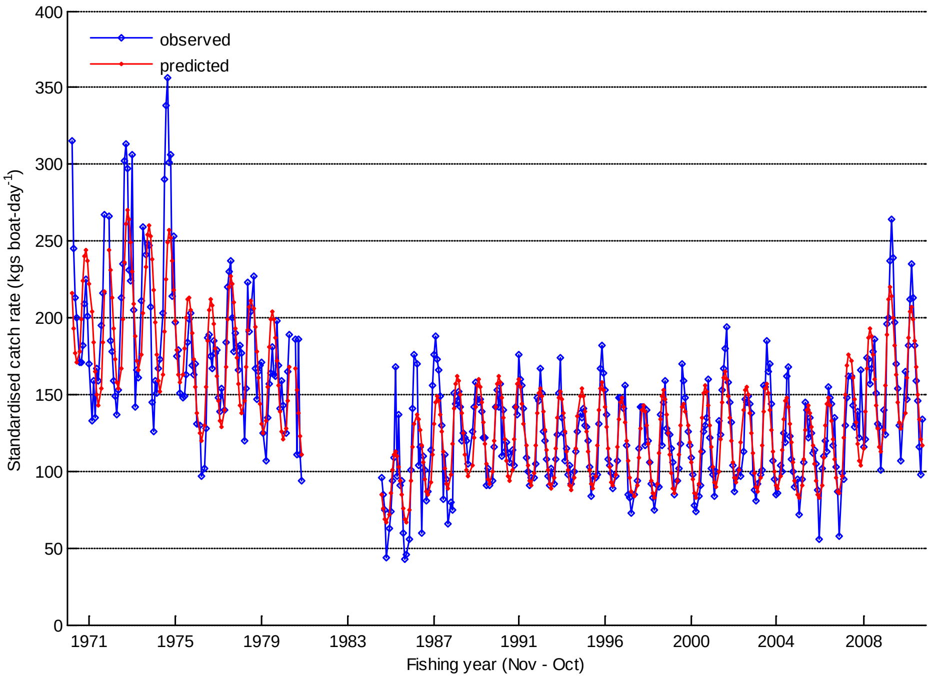


Figure 17-53. Delay difference model 1 predicted fit (red) to the whole-fishery standardised catch rates (blue). Y-axis catch rate (CPUE) unit was kg boat-day^{-1}.

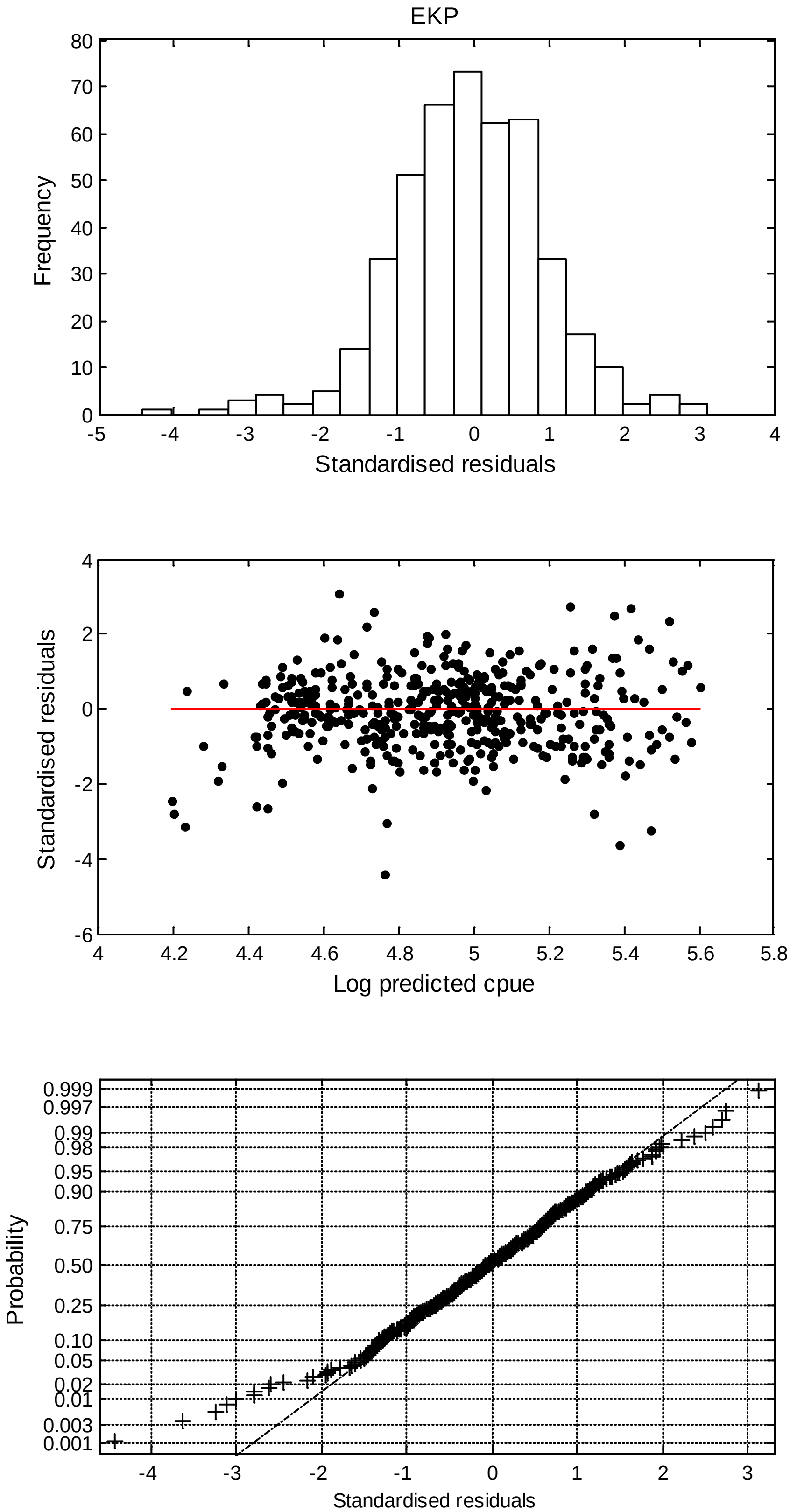


Figure 17-54. Standardised residuals from delay difference model 1 fit to the whole-fishery standardised catch rates.

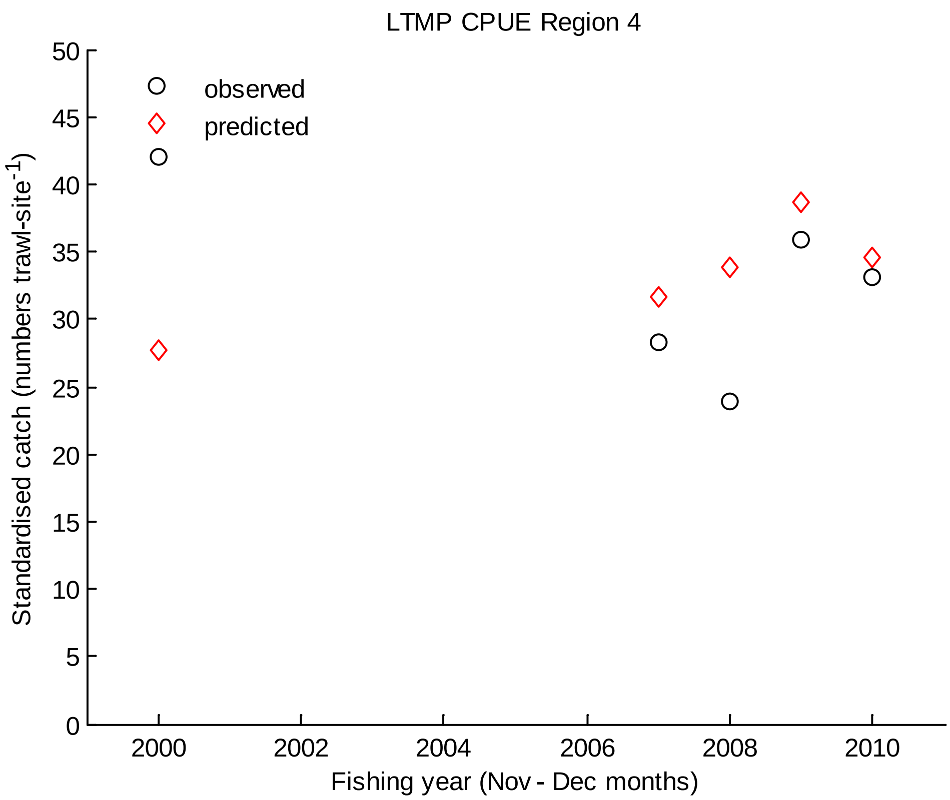


Figure 17-55. Delay difference model 1 predicted fit to the monitoring standardised catch rates for region 4 (Qld inshore shallow waters).

Table 17-18. Parameter estimates for the delay difference models and bias-corrected bootstrap 95% confidence intervals between brackets from 1000 bootstraps. The MEY estimates were based on Table 17-10.

Estimate	**Model 1**	**Model 2**	**Sensitivity 1**	**Sensitivity 2**
$-\log l$	-251.93	-252.14	-257.11	-263.3
Steepness *h*	0.27 (0.24 : 0.28)	0.25 (0.23 : 0.27)	0.32 (0.3 : 0.35)	0.27 (0.24 : 0.34)
R_0 / 10^8	7.83 (6.39 : 12.03)	10.23 (7.54 : 14.63)	4.89 (4.46 : 8.44)	12.12 (6.15 : 35.6)
μ	2.15 (1.99 : 2.28)	2.27 (1.87 : 2.43)	2.28 (2.1 : 2.39)	2.1 (1.96 : 2.25)
κ	1.75 (1.51 : 2)	1.4 (1.13 : 3.57)	1.47 (1.32 : 1.77)	1.95 (1.63 : 2.26)
M (month $^{-1}$)	0.18 (fixed)	0.21 (0.15 : 0.23)	0.18 (fixed)	0.18 (fixed)
MSY (t)	2849 (2451 : 3449)	2962 (2479 : 3959)	2893 (2714 : 3462)	4463 (2822 : 35995)
E_{MSY} (boat-days yr^{-1})	27030 (20131 : 36165)	28167 (20315 : 42081)	26364 (22339 : 35985)	59357 (31771 : 543417)
MEY (t)	2272 (2065 : 2649)	2363 (2086 : 2977)	2341 (2270 : 2677)	2828 (2051 : 20081)
E_{MEY} (boat-days yr^{-1})	13974 (11792 : 17129)	14664 (11854 : 19954)	13422 (12301 : 16829)	21563 (14250 : 165317)

17.9 SUPPLEMENTARY MATERIAL 4: ECONOMIC DATA

Table 17-19 and Table 17-20 summarise the different variables for annual vessel costs (W_r) and average total investment per vessel (K_y). The values represent the 2010 Queensland EKP fleet and were used to parameterise fixed-cost equation. The fixed costs do not relate to fishing effort, but rather annual costs to make a trawl vessel operational. Further detail on these cost variables are contained within the economic questionnaire. Table 17-21 reports the change in economic values with vessel standardised hull units (*SHU*).

Table 17-19. Description of average annual vessel costs (W_r) from Queensland.

W_r variables	**$ per boat per year**	**Proportion of sum(W_r)**
Motor vehicle fees	811	0.02
Banking charges	537	0.01
Port/jetty/etc. charges	3323	0.07
License & industry fees	5270	0.11
Insurance costs	18122	0.39
Other boat fees	606	0.01
Meetings, travel, etc.	2491	0.05
Other expenses	2818	0.06
Office consumables	324	0.01
Electricity	2533	0.05
Communications	4639	0.1
Vehicle running costs	4695	0.1
Total (sum)	**46170**	**1**

Table 17-20. Description of average investment value per vessel ($K_{r,y}$) from Queensland.

$K_{r,y}$ variables	**$ per boat per year**	**Proportion of sum($K_{r,y}$)**
Primary boat hull	512889	0.76
Electronics	79199	0.12
Jetty/berth/mooring	13364	0.02
Sheds	23097	0.03
Cold room/freezers on boat	20859	0.03
Vehicle value	24182	0.04
Total (sum)	**673590**	**1**

Table 17-21. Mean economic parameters by standardised hull unit (*SHU*).

SHU	$\log\left(c_{K_r}\right)$	$c_{F_{1..4}}$	c_{F_5}	c_{F_6}	$\log\left(W_r\right)$	$\log\left(K_{r,y}\right)$
25	5.437	453.51	467.45	630.8	9.83	11.8
30	5.552	503.02	518.48	699.66	10.06	12.13
35	5.667	526.84	543.03	732.8	10.26	12.45
40	5.782	538.31	554.85	748.74	10.45	12.77
45	5.896	543.82	560.53	756.41	10.61	13.1
50	6.011	546.48	563.27	760.11	10.74	13.42
55	6.126	547.75	564.59	761.88	10.85	13.74
60	6.24	548.37	565.22	762.74	10.94	14.07
65	6.355	548.66	565.52	763.15	11.01	14.39

17.10 SUPPLEMENTARY MATERIAL 5: MODEL PROJECTION DATA

17.10.1Monthly fishing patterns

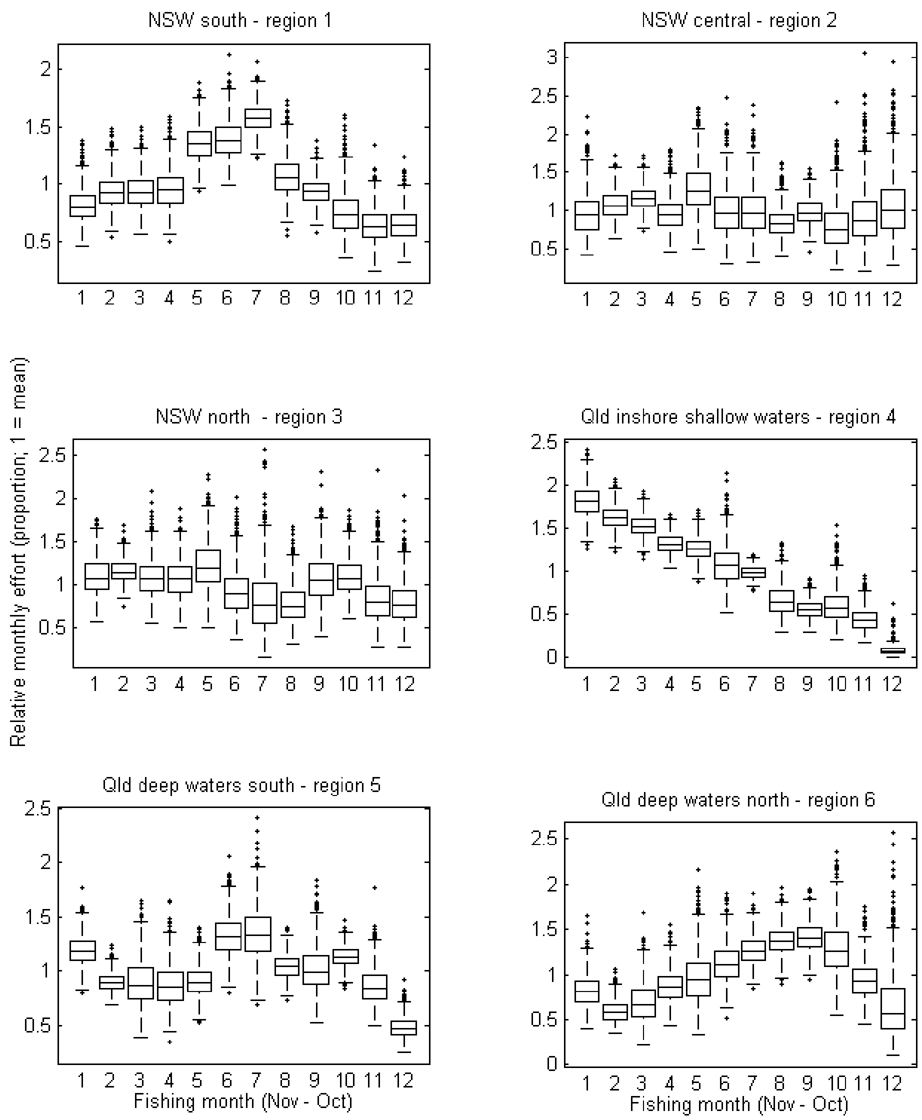


Figure 17-56. Status quo effort patterns between 2006 and 2010: Box-plots of region-by-month variation in fishing effort simulated in future projections for MSY/MEY reference points and harvest strategies. The plots display the simulated distributions around their medians (line in the middle of each box). The top and bottom of each "box" are the 25th and 75th percentiles, respectively. Variations beyond the whisker length (≈2.7σ) are marked as extremes.

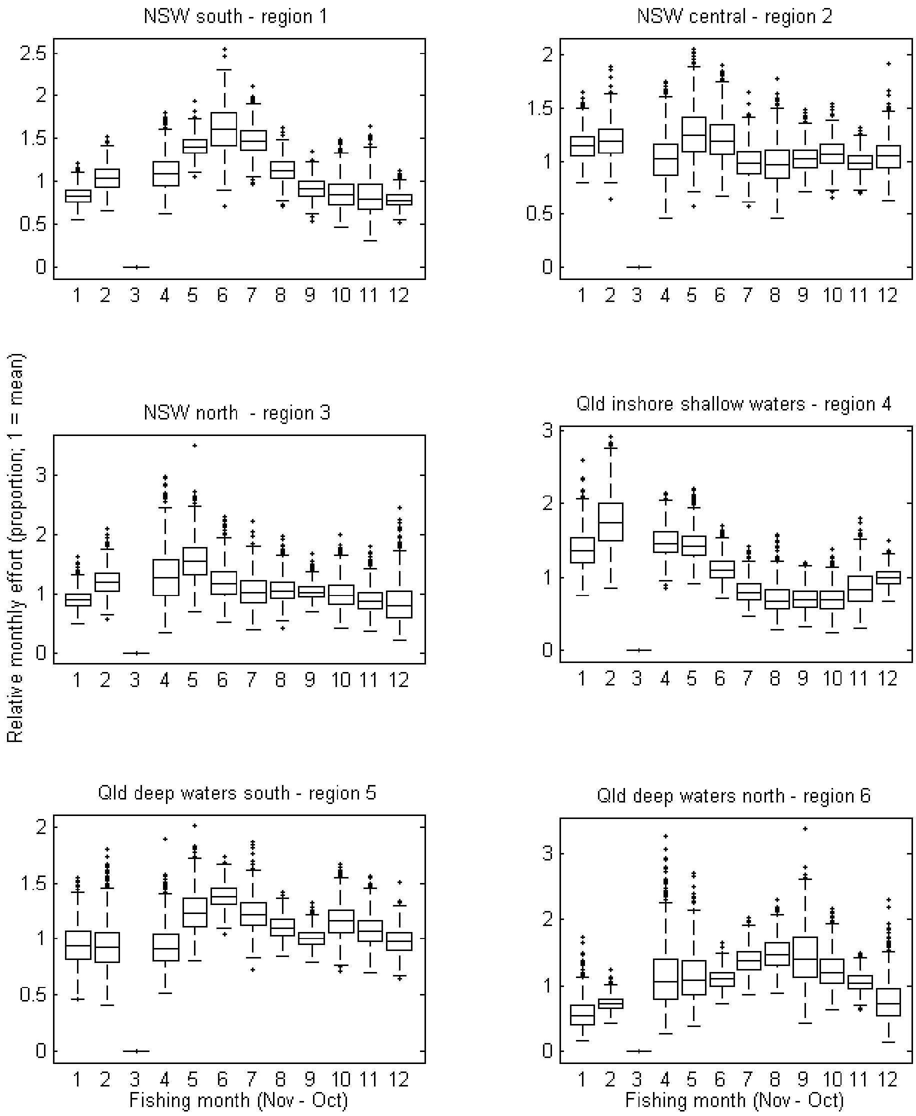


Figure 17-57. Effort patterns with January closure: Box-plots of region-by-month variation in fishing effort simulated in future projections for MSY/MEY reference points and harvest strategies. The plots display the simulated distributions around their medians (line in the middle of each box). The top and bottom of each "box" are the 25th and 75th percentiles, respectively. Variations beyond the whisker length (≈2.7σ) are marked as extremes.

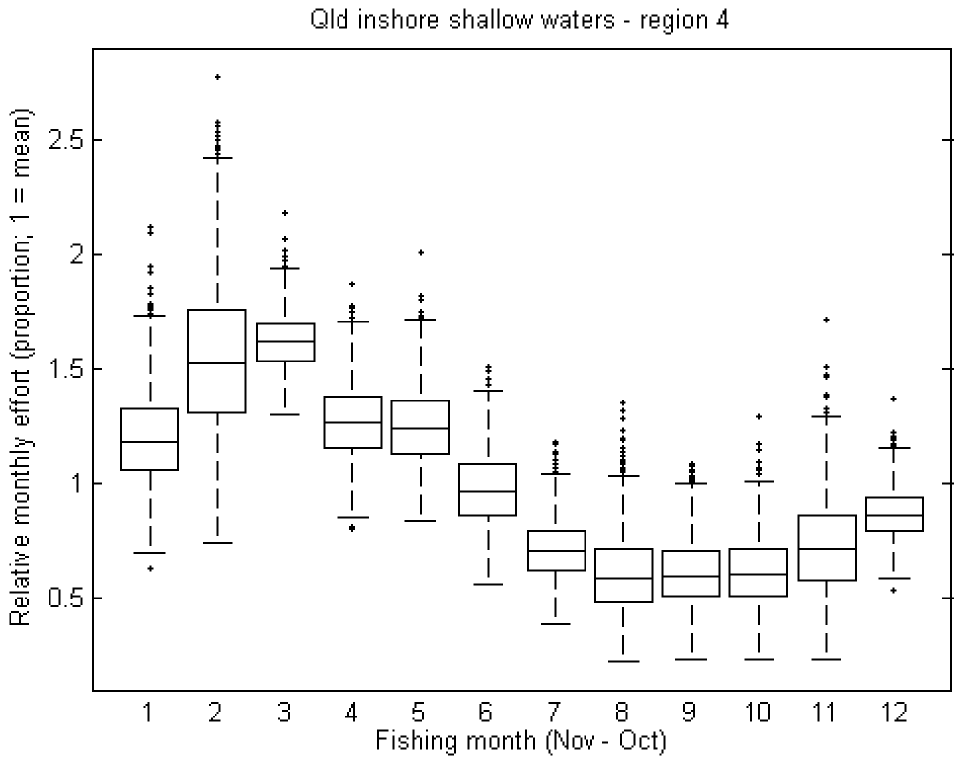


Figure 17-58. Queensland inshore effort pattern with no closure: Box-plots of region-by-month variation in fishing effort simulated in harvest strategies. The plots display the simulated distributions around their medians (line in the middle of each box). The top and bottom of each "box" are the 25th and 75th percentiles, respectively. Variations beyond the whisker length (≈2.7σ) are marked as extremes.

17.10.2 Fishing effort movement matrix

The fishing movement matrix p defined the proportions of monthly effort redistributed when regions were closed to fishing due to low catch rates (Table 17-12, management procedures 6 and 7, footnote c):

$$p = \begin{bmatrix} 0 & 0.41 & 0.50 & 0 & 0 & 0 \\ 0.30 & 0 & 0.54 & 0 & 0 & 0 \\ 0.25 & 0.41 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.41 & 0.35 \\ 0 & 0 & 0 & 0.57 & 0 & 0.29 \\ 0 & 0 & 0 & 0.62 & 0.34 & 0 \end{bmatrix}.$$

The probabilities p were calculated from logbook tallies of each vessel's regional pattern of fishing. The movement matrix was structured in two parts, rows 1 to 3 for New South Wales and rows 4 to 6 for Queensland (three management regions for each State). The States' jurisdiction fishing efforts were simulated separately. If low catch rates triggered a region (row p) closure, fishing effort e_{r_closed} was reallocated to the State's two open regions based on row probability $p_{r\_closed \rightarrow r\_open}$. If two regions were closed to fishing, each closed region's effort e_{r_closed} was reallocated to the open region based on the row probability $p_{r\_closed \rightarrow r\_open} + p_{r\_closed \rightarrow r\_open} \times p_{r\_closed \rightarrow 2nd\_r\_closed}$.

18 Appendix 6. Yield and value per recruit assessment of the proposed North Reef closure on eastern king prawns (Objective 3)

This section addresses Objective 3 *Develop (computer) models of the eastern king prawn fishery that evaluate alternative harvest strategies, as identified by the fishery managers and fishers, and provide advice on the efficacy of each strategy in achieving biological and economic management objectives.*

18.1 Abstract

Yield and value per recruit were used to examine the effects a proposed closure, identified by fishers, in the northern part of the EKP fishery in offshore waters of the central Queensland coast near North Reef (~23^{o}S). Prawn samples from inside the proposed closure had a modal age frequency distribution of 0.5-1.0 years, which equates to commercial grades of 10 to 30 prawns per pound. Tagging showed the prawns migrate out of the area and head east-northeast towards the Swain Reefs. If the area was closed it would likely increase the age at which the prawns are first caught in the region to 0.75-1.25 years. Estimates of the instantaneous rate of fishing mortality (*F*) based on the tagging data ranged from 0.26-0.53 per year, which is quite low. In general, closures are more beneficial, in terms of increasing yield and value, when stocks are heavily fished. The analyses indicate that both yield and value would be reduced if the closure was implemented. This is because the size and age of the prawns at first capture are already at, or close to, that required for maximising yield and value. Consequently, we recommend the closure not be implemented.

18.2 Introduction

Recently, some trawl fishers operating in the northern part of the eastern king prawn fishery (i.e., 22^{o}S-24^{o}S) have expressed concern that prawns are harvested at sizes that are ‘too small’ (i.e., below the size required to maximise yield), particularly in the vicinity of North Reef. To address the problem the fishers have delineated an area closure (Figure 18-1).

Determining the ‘best’ size or age at which to harvest fished stocks, including penaeid prawns, is a common and important objective in fisheries management. Allocating an incorrect minimum legal size or age at first capture can result in the catch falling below the maximum sustainable yield (MSY). This is technically referred to as growth overfishing (Haddon 2001; Hilborn and Walters 1992; Sparre and Venema 1998) and can occur by harvesting below or above the best size or age at first capture, although it is almost always the former.

For prawn fisheries, deriving the best size or age at first capture can be thought of as balancing act between harvesting too early in the season or too late – the positive effects on the stock biomass, due to recruitment and growth, have to be balanced against the negative effects due to fishing mortality and natural mortality. In terms of MSY, the best size or age at first capture is not fixed, but varies with fishing mortality. However, when fishing mortality is low, the influence of the size or age at first capture on yield is also low. Another way of thinking about this is that implementing a size or age at first capture that results in MSY is more important for heavily exploited stocks than for lightly exploited stocks because if fishing mortality is low, the size or age at which fishing mortality starts to impact the population is inconsequential.

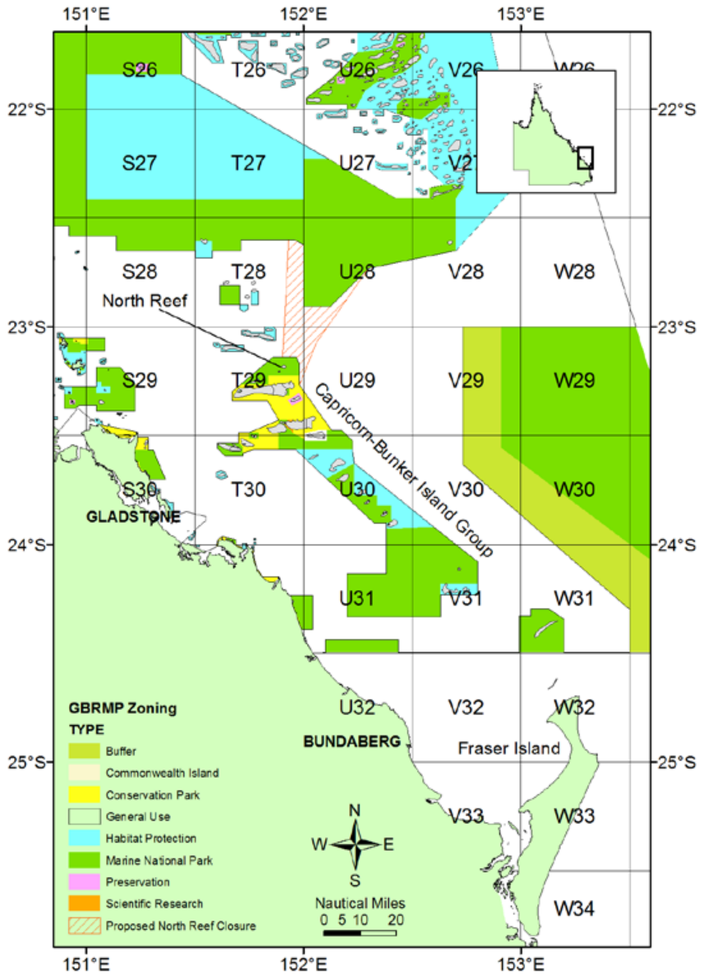


Figure 18-1. The proposed trawl closure near North Reef designed by fishers.

Penaeid prawns generally have relatively fast growth and a short life span (~ 1-2 years, Garcia and Le Reste 1981). Thus, the range in size or age at first capture that results in MSY is relatively narrow, so if the stock is left unharvested for more than a few months, the biomass may decline to such an extent (due to natural mortality) that the catch falls below MSY. The size or age at first capture can be largely controlled by regulating a) mesh size, b) areas open to fishing, and c) the timing and duration of fishing. Growth overfishing can also be controlled by managing fishing effort (which is generally a direct measure of fishing mortality), although historically this has not been a management option for Queensland prawn stocks.

It is unknown whether the proposed North Reef closure would result in an increase in yield or value. Lucas (1974; 1975) studied the growth and mortality rates of EKP in southeast Queensland in the early 1970s and estimated the best size at first capture. Although the fishery has expanded since, and we know have a more comprehensive understanding of the species' growth rate (Glaister *et al.* 1987; Lloyd-Jones *et al.* 2012), Lucas estimated that yield would be maximised by first harvesting at a commercial size grade of 30 prawns per pound (~15 g or about 29 mm CL). This is smaller than the majority of EKP sampled from North Reef, but larger than the majority from Fraser Island (Figure 15-5). It is also much smaller than the size range of prawns sampled from the Swain Reefs. It is also larger than the majority of EKP trawled in Moreton Bay using commercial mesh (Courtney *et al.* 1995).

In this chapter yield and value per-recruit (Beverton and Holt 1957) analyses were used to evaluate the likely effects of the proposed North Reef closure. The results can be used by the fishery's managers and stake holders to evaluate the costs and benefits of the closure in this region and possibly other areas in the fishery where growth overfishing may be of concern.

18.3 Materials and methods

18.3.1 Yield per recruit

Yield-per-recruit is a well-established approach by Beverton and Holt (1957) based on a standard steady-state model that is widely used for stock assessment and investigating the effects of different sizes or ages at first capture on yield. Yield-per-recruit requires information on growth and mortality rates (i.e., natural mortality and fishing mortality), and length-weight relationships. In a steady state fishery, yield-per-recruit can be estimated by:

$$Y/R = \exp(-M(t_c - t_r)) \sum_{i=t_c}^{i=t_l} \left\{ (F/(F+M)) \exp(-(F+M)(i-t_c)) \, (1-\exp(-(F+M)))W_i \right\}$$

where, Y = steady state yield of the fishery, R = number of recruits, W_i = mean weight of fish aged i, t_r = age at recruitment to fishable stock, t_c = actual age of first capture, t_l = maximum age of fish in stock. Some rigorous assumptions underlie the equilibrium yield-per-recruit:

(i) recruitment is constant, yet not specified (hence the expression yield-per-recruit),
(ii) all fish (prawns in the present study) of a cohort are hatched on the same date,
(iii) fishing and natural mortalities are constant over the post-recruitment phase, and
(iv) fish older than t_l make no contribution to the stock.

In most commercial fisheries it is the monetary value of the catch that is of interest, rather than the yield or weight, and therefore price data were substituted for weight-at-size/age in order to evaluate different sizes and ages at first capture.

18.4 Results

18.4.1 Growth

Several studies have described von Bertalanffy growth for *M. plebejus* (Table 18-1). Early estimates of K and L_∞ may have been slightly biased as tagging studies tended to focus on inshore areas, such as Moreton Bay, where the prawns are relatively small and probably growing at their fastest rate (e.g., high K). Earlier studies were also dominated by observations from New South Wales and as such were obtained from relatively high latitudes, which we now know also influence the estimate of K.

In the 1980s the fishery expanded northwards (i.e., north of 25°S) and further offshore. The recent analysis by Lloyd-Jones *et al.* (2012) produced a more comprehensive description of growth because it utilised all available tagging data from New South Wales and Queensland and derived covariates for latitude and season. K (per year) was found to decline with increasing latitude by 0.0236 and 0.0556 per degree, for males and females respectively. Seasonally, growth rates peaked in January and declined to minimum in July.

Table 18-1. Summary of von Bertalanffy growth parameters K and L_∞ put forward for eastern king prawns.

Author	**Male K**	**Male L_∞ (mm CL)**	**Female K**	**Female L_∞ (mm CL)**	**Comment**
Lucas (1974)	0.1 per week or 5.2 per year	40.00	0.1 per week or 5.2 per year	49.00	High K values possibly reflect relatively young, fast growing stages the fishery focused on in the 1970s, before expanding offshore to include larger, older slower-growing stages.
Glaister *et al.* (1987)	0.0595 per week, 0.258 per month or 3.094 per year	45.44	0.0483 per week or 0.2093 per month or 2.5116 per year	59.53	Predominantly NSW data (i.e., high latitudes), possibly explaining the relatively low K values.
Die *et al.* (1999)	0.34 per month or 4.08 per year	41.00	0.25 per month or 3.0 per year	53.00	Fabens model based on combined Glaister data and QLD 1990-91 data.
Lloyd-Jones James estimate	0.204 per month or 2.45 per year	44.90	0.169 per month or 2.03 per year	57.40	Includes Montgomery data 1991-1992, and 1990-91 QLD data.
Lloyd-Jones *et al.* (2012)	1.43 per year (@25°S degrees S)	46.70	1.46 per year (@25°S degrees S)	61.10	Includes Montgomery data 1991-1992, and 1990-91 QLD data.

The precise growth parameters used for yield-per-recruit were K=1.457 $year^{-1}$ and L_∞= 47.01 mm CL for males, and K=1.616 $year^{-1}$ and L_∞= 61.20 mm CL for females (Figure 18-2), based on a latitude of 22.5°S (i.e., about half way between North Reef and the Swain Reefs).

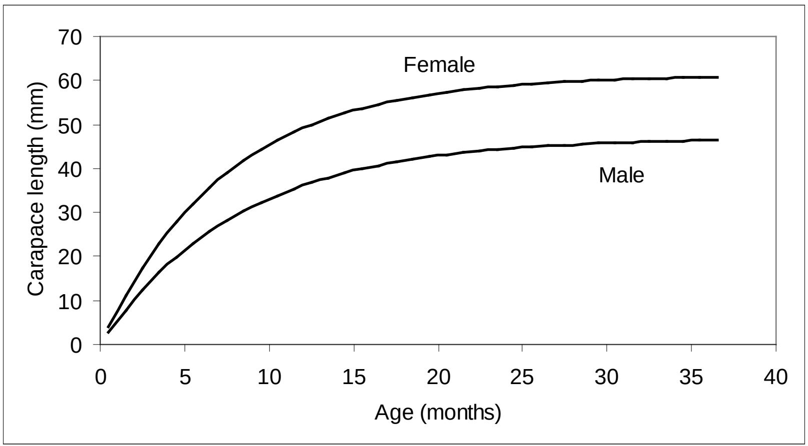


Figure 18-2. EKP growth curves used for the yield-per-recruit analysis.

Length-frequency data collected from the 83 sites in 2009 and 2010 (Figure 15-5) provided information on the size (and derived age) of prawns inside the proposed North Reef closure and other locations. Four size or age distributions for each sex were considered for yield-per-recruit: 1) east of Fraser Island, 2) inside the North Reef proposed closure, 2) midway between North Reef and the Swain Reefs, (Figure 18-3), referred to as 'mid area', and 4) Swain Reefs. The effects of the closure were analysed by varying the size or age at which fishing mortality first impacts the population, based on the size of prawns from the different areas. While prawn lengths were measured directly, ages were derived using the inverse von Bertalanffy growth equation:

$$t(L) = t_o - \frac{1}{K} ln(1 - \frac{L}{L_\infty})$$

The parameter t_o is often ignored prawn growth studies and was assumed a value of zero herein. The smallest prawns sampled, which were from Fraser Island, were mostly in the size range of 20-30 mm CL, which equates to ages of 3-6 months (Figure 18-3). In terms of commercial grades, these prawns were generally smaller than 21-30 prawns per pound (i.e., smaller than the smallest commercial grade considered in section 15.4.3), with a significant proportion smaller than 50 prawns per pound (i.e., smaller than about 9 g).

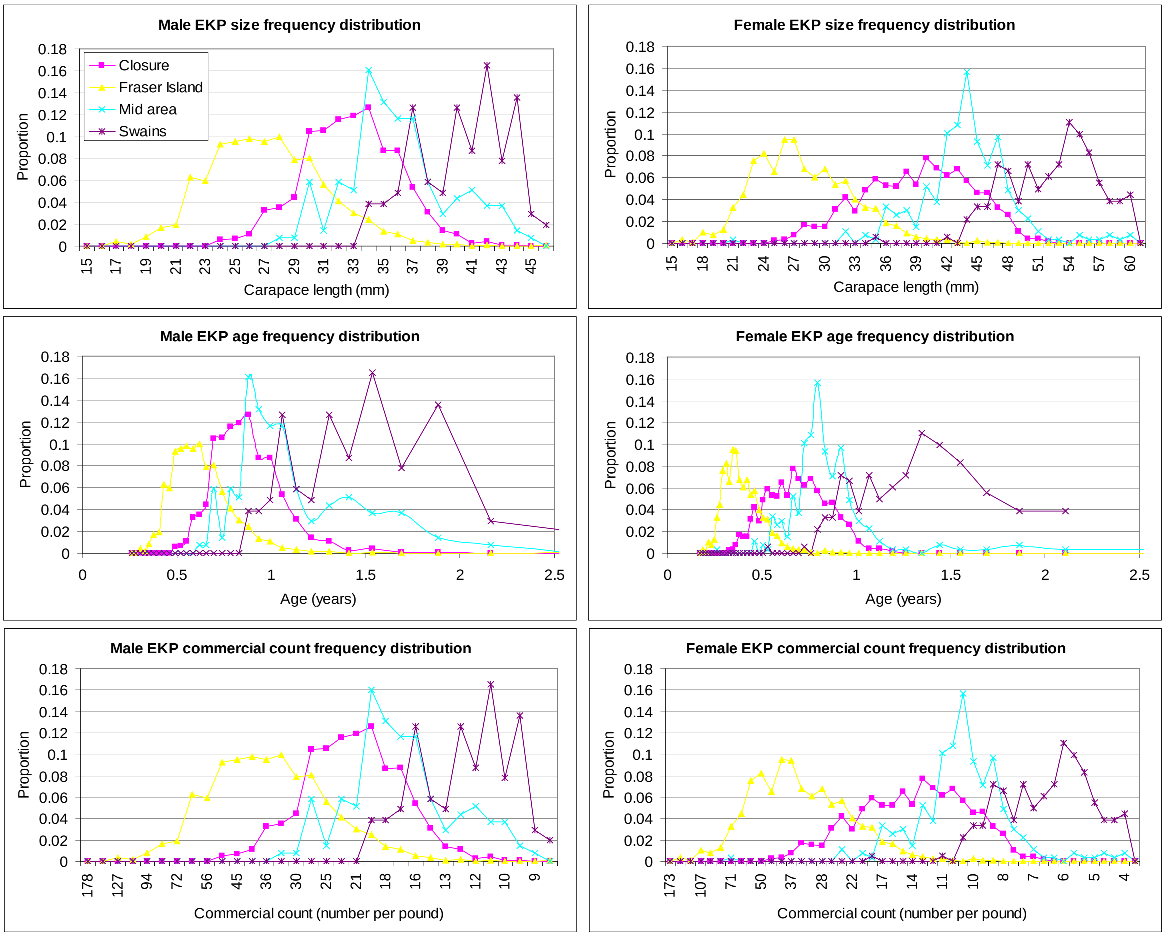


Figure 18-3. Carapace length (upper), age (middle) and commercial grade frequency distributions of eastern king prawns from 83 sites in the northern part of the fishery, including within the proposed North Reef closure. Note that as males rarely grow larger than about 45 mm CL, they do not contribute to the large commercial grades.

In the proposed North Reef closure, males were mostly in the size range 30-40 mm CL, which equates to ages of about 6-12 months, while females were mostly 30-50 mm CL, which equates to a similar age range (Figure 18-3). In this area, males contributed mainly to catch grades of 21-30 prawns per pound and 16-20 prawns per pound. As the females were larger than males, they contributed to larger grades, particularly 10-15 prawns per pound and 8-10 prawns per pound.

In the 'mid area' males were mostly in the size range 33-43 mm CL, which equates to ages of about 8-15 months. Most of these prawns are marketed in the 16-20 count per pound grade. Females in the 'mid area' were larger, mainly 40-50 mm CL, but of similar ages to the males. The females fall in the 8-10 prawns per pound commercial grade.

The largest prawns were from the Swain Reefs, where males were mostly 35-45 mm CL, while females were 45-60 mm CL (Figure 18-3). These prawns were predominantly 12-24 months old. Males mainly contributed to the 10-15 prawns per pound grade, while females almost exclusively comprised the very large grades of 6-8 prawns per pound and fewer than 6 prawns per pound.

The broad range in size and age at which the prawns are harvested is apparent from the data. Some of these sizes/ages may be smaller/younger than what is required to achieve MSY. It is also apparent that the number of prawns surviving past 24 months of age is extremely low. It is also noteworthy that prawns smaller than the minimum modes presented here are harvested in Moreton Bay, and possibly other shallow inshore areas of New South Wales.

18.4.2 Mortality rates

We used a value of 2.4 per year (reported as 0.5 per week or 0.2 per month) for the instantaneous rate of natural mortality (M), after Lucas (1975). Estimates of the instantaneous rate of total mortality (Z) were obtained by quantifying the decline in the number of recaptured tagged prawns over several months (Hilborn and Walters 1992) following the North Reef releases in January 2009. The subsequent declining slope of the graph provides an estimate of Z and since $Z = M + F$ (Sparre and Venema 1998), an estimate of the instantaneous rate of fishing mortality (F) can be derived.

During the tag-recapture experiments, prior to being placed in the release cage (Figure 15-1), tagged prawns were retained in seawater for observation. Any morbid or dead prawns were removed and hence, not included with the releases. The proportion of prawns dying immediately after tagging is referred to as the instantaneous rate of tagging mortality (α) (Hilborn and Walters 1992). Since we removed dead and dying tagged prawns prior to release, we have assumed that any residual tagging mortality is likely to be negligible. In any case, the value of α is of no consequence as it does not affect the slope of the graph of the recaptures over time (i.e., Z), but rather where the slope crosses the y-axis.

From 22-24 January 2009, 1474 prawns were tagged and released at 7 sites near North Reef and over the following 18 months (i.e., 542 days) 63 (i.e., 4.3%) were recaptured by the fleet. Two prawns were recaptured about one month after release (on 28th February 2009) and another two captured in March 2009. Four prawns were recaptured in April 2009. In order to allow the prawns time to recover from being tagged and released, assume normal behavioural patterns, disperse and become fully exposed to trawl effort in the region, these first eight early recaptures in February, March and April were ignored, and the decline in recaptures was quantified from May 2009 onwards.

There is no specific period at liberty which results in a more robust mortality rate estimate from tagging experiments. For penaeid prawns, periods less than two months are probably too short to demonstrate a definitive decline in recapture rate, while negligible additional useful information generally results for periods greater than about two years. For this reason, two periods were considered for quantifying *Z*; the first was six months from May 2009 to November 2009, the second was 13 months from May 2009 to June 2010. The shorter period probably provides the more robust estimate because it has a higher number of recaptures (i.e., more observations) per unit of time, and because the slope derived from the longer 13-month period may be heavily influenced by only one or two recaptures after a year or so. A single recapture with a long period at liberty affects the slope more than a single recapture with a short period at liberty. This is because most observations have short periods at liberty (i.e., less than six months). Nevertheless, when two such periods are considered they provide some understanding of the likely range in values for *Z*, and hence, *F*.

Estimates of *Z* were derived using a GLM of the recapture data. The response variable was the raw (i.e., untransformed) number of recaptures in a given calendar month (i.e., May 2009, June 2009, July 2009, … June 2010), with time being the only explanatory variable. Monthly effort in the region was derived from logbook data and used in the model as an offset (log transformed number of boat-days). The model assumed a Poisson distribution with logarithm link.

Predicted recaptures over time and the derived regression slopes are provided in Figure 18-4. Over the six months from May to November 2009, *Z* was estimated to be 2.93 per year, resulting in an *F* value of 0.53 per year. Over the longer 13-month period, from May 2009 to June 2010, *Z* was estimated to be 2.66 per year, resulting in an *F* value of 0.26 per year. Note the standard errors of the adjusted means increase with time, probably due to the declining number of recaptures. The estimates of fishing mortality *F* are low – about 10-20% of the natural mortality rate *M*, which indicates the stock is lightly exploited in the area.

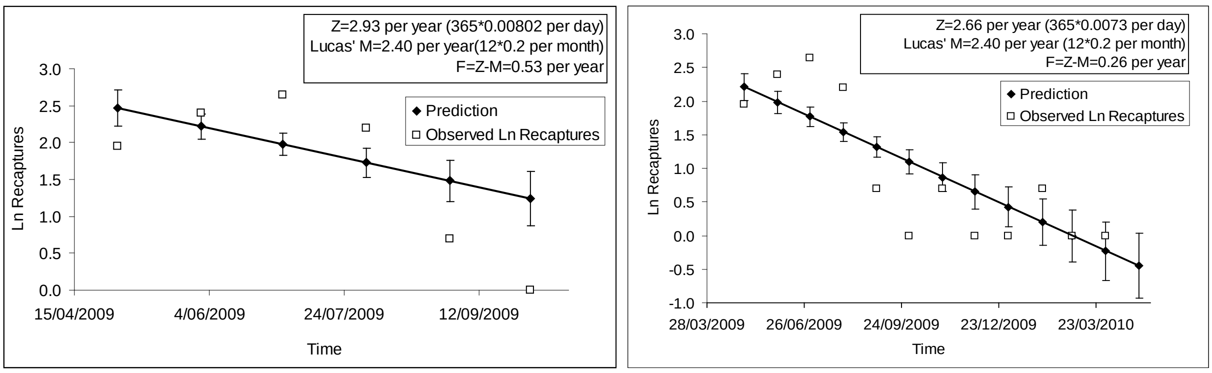


Figure 18-4. Estimates of the instantaneous rates of total mortality (*Z*) and fishing mortality (*F*), based on the decline in recaptured tagged eastern king prawns over six months (left) and 13 months (right).

18.4.3 Yield per recruit results

The prawns were assumed to recruit to the fishable stock at 3 months of age (i.e., t_r = 0.25 years) and the maximum age of a prawn in the stock t_l was assumed to be 4 years. A combined-sex yield per recruit (Figure 18-5) indicated that highest yields would be obtained by harvesting prawns at ages between 0.3 and 0.7 years (i.e., about 4-8 months) and at relatively high fishing mortalities (i.e., *F* values larger than about 2.0 per year). These ages equate to relatively small commercial grade counts (i.e., 28-140 prawns per pound for males and 10-50 prawns per pound for females). For prawns older than about 0.5 years, yield declines markedly with increasing age at first capture, especially at high fishing mortalities.

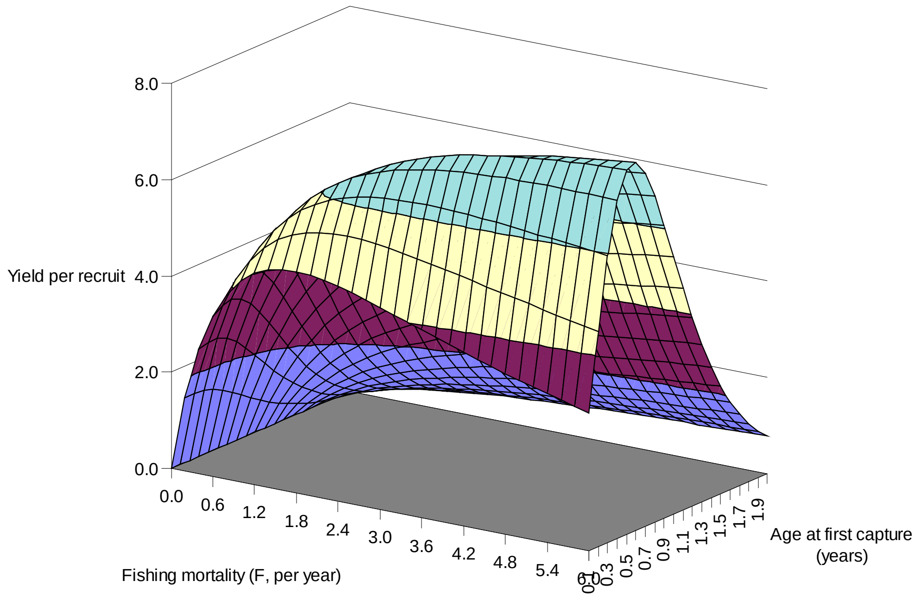


Figure 18-5. Surface plot of yield per recruit for eastern king prawns (sexes combined). Recent estimates of the fishing mortality rate based on the tag-recapture data range from 0.26 to 0.53 per year.

'Slices' through the yield surface plot (Figure 18-5) at specific fishing mortality rates show the higher yields associated with the higher fishing mortalities (i.e., 2.4 and 4.0 per year) (Figure 18-6). At fishing mortality rates of 0.2 and 0.6 per year, which encompass the recent tagging-based estimates, yields are significantly lower. The slices also show the influence of a minimum size or age at first capture diminishes with declining fishing mortality. At higher fishing mortalities (i.e., *F* values of 2.4 and 4.0 per year) clear peaks in yield occur at specific sizes or ages at first capture, but at the lower fishing mortalities (i.e., *F* values of 0.2 and 0.6 per year) no clear peaks are discerned and comparatively high yields are obtained over a broad range of ages.

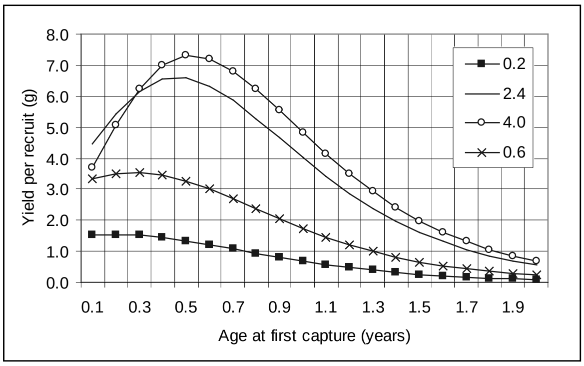


Figure 18-6. Yield per recruit of eastern king prawns (sexes combined) at four fishing mortality rates (0.2, 0.4, 2.4 and 4.0 per year). Yields generally peak at ages at first capture between 0.3 and 0.7 years.

An additional stochastic analysis of the age and size at first capture was undertaken using an Microsoft Excel spreadsheet model of the Beverton and Holt (1957) yield per recruit which considered uncertainty in the population parameters *M*, *K* and weight at L_∞ (referred to as W_∞). Distributions of *M* and W_∞ were normally distributed while *K* was lognormal, based on their means and standard deviations. The age at first capture which resulted in maximum yield was estimated 1000 times using the Excel add-on software program Crystal Ball. Each time yield is calculated a value of *M*, *K* and W_∞ is selected from their distributions. As *K* and L_∞ (~W_∞) are negatively correlated (Kirkwood and Somers 1984), a correlation of -0.4 was applied to these two distributions. The analysis was undertaken assuming a high value for fishing mortality (F = 5.0 per year) and was undertaken for each sex separately, producing a distribution of ages at first capture (Figure 18-7).

The age at which yield is maximised for females is 0.55 years (6-7 months), which equates to 36 mm CL, an individual weight of 27 g or 17 prawns per pound (Figure 18-7). A similar mean of 0.56 (6-7 months) years was derived for males, however, at this age males are considerably smaller than females at about 26 mm CL, and weigh about 11 g or 43 prawns per pound.

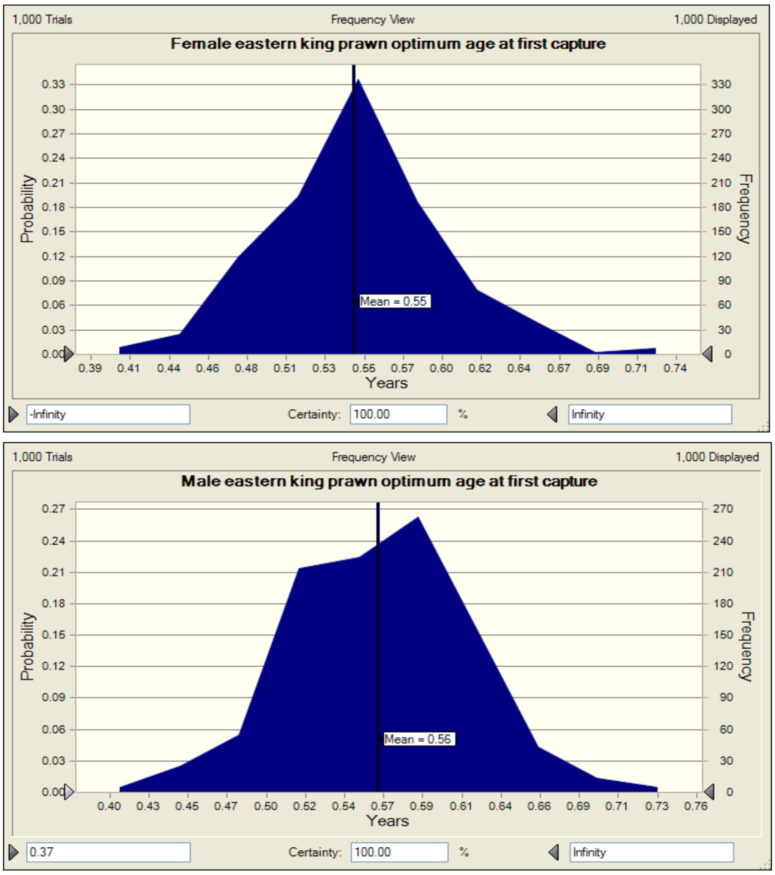


Figure 18-7. The optimum age at first capture for female (above) and male (below) eastern king prawns. These age distributions were derived by re-sampling from distributions of *M*, *K* and W_∞.

18.4.4 Value per recruit

Value per recruit was estimated for males and females separately. Price information can have a significant influence on value per recruit, as price fluctuations influence the value of different size and age classes. Price information was collated from data provided by Mr. Martin Perkins (Queensland Seafood Marketers Association) for "king prawns" from the central Queensland and the Fraser-Burnett regions from October 2010 to June 2011. As these data only provided information on commercial grades 21-30 prawns per pound and larger, additional information for the small grade of 30-40 prawns per pound was obtained from a discussion with Moreton Bay commercial fisher Michael Woods (9/4/2013). The prices refer to wharf price, or the price received by the fisher from the first sale point. The relationship between price and prawn weight (Figure 18-8) can be summarised as follows. The average wharf price of eastern king prawns weighing:

- less than 11 g (i.e., smaller than about 40 prawns per pound) are too small for sale and have no market value.
- 11-15 g (i.e., commercial grade of 30-40 prawns per pound) is $8.50 per kg.
- 16-22 g (i.e., 20-30 per pound) is $11.50 per kg.
- 23-45 g (i.e., 10-20 per pound) is $13.50 per kg.
- 46-57 g (i.e., 8-10 per pound) is $17.70 per kg.
- 58-76 g (i.e., 6-8 per pound) is $19.30 per kg.
- more than 76 g (i.e., U6 with fewer than 6 prawns per pound) is $21.30 per kg.

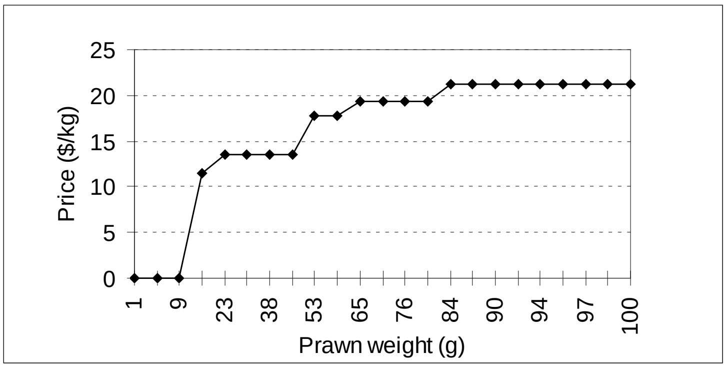


Figure 18-8. Summary of prices data for different sizes of eastern king prawns used in the value per recruit analysis.

Value per recruit results are provided for a range fishing mortality rates (0.27, 0.42 and 2.4 per year, Figure 18-9). The results indicate that, similar to yield, higher value per recruit could be achieved at fishing mortality rates that are higher than those likely to be operating at present in this northern part of the fishery.

At the 2009-2010 low fishing mortality rates (i.e., 0.26-0.53 per year, Figure 18-4), value per recruit for males peaks at an age at first capture of 0.6 years (Figure 18-9). At this age males weigh about 12 g (i.e., commercial grade of 30-40 prawns pound). At the higher fishing mortality rate of 2.4 per year, value per recruit increases by 30-40% and peaks at an age at 0.7-0.9 years. At these ages males weigh 15-22 g (i.e., 20-30 prawns per pound).

At the 2009-2010 relatively low fishing mortality rates, value per recruit for females peaks at 0.4-0.5 years (Figure 18-9) – slightly younger than for the males, possibly because females have a higher von Bertalanffy growth coefficient K. At these ages females weigh 15-20 g (i.e., commercial grade of 20-30 prawns per pound). At the higher fishing mortality rate of 2.4 per year, female value per recruit would increase by 20-50% and peak at 0.5-0.8 years, which corresponds to female weights of 20-50 g (i.e., 10-20 prawns per pound).

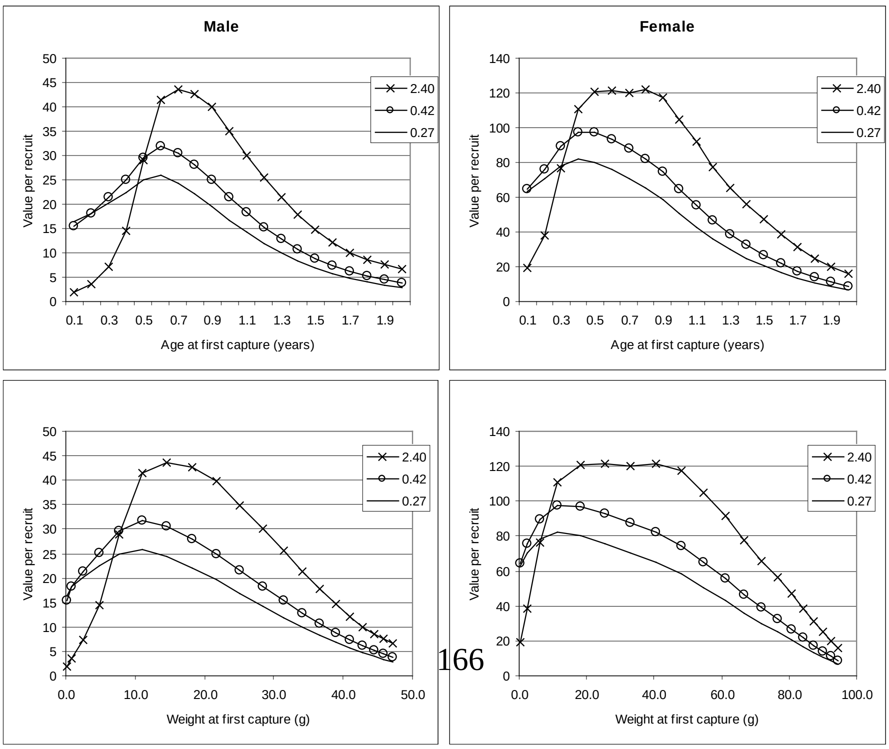


Figure 18-9. Value per recruit for female and male eastern king prawns, at three fishing mortality rates. Note higher value per recruit would be achieved at a higher fishing mortality rate than that currently applied in this part of the fishery.

The large difference in maximum attainable size (i.e., weight at L_∞) for males and females is apparent in Figure 18-9 and most likely explains the difference in the y-axis scales, where females attain higher value per recruit. Males don't grow to the large sizes that females can attain. The largest commercial grade for males was 8-10 prawns per pound with a corresponding price of $17.70 per kg, while females exclusively contributed to the two largest grades (i.e., 6-8 prawns per pound and fewer than 6 prawns per pound), with prices of $19.30 per kg and $21.30 per kg, respectively.

18.5 Discussion

The yield and value per recruit are heavily affected by the relatively low fishing mortality estimates derived from the tagging data (Figure 18-4). The *F* estimates (i.e., 0.26 and 0.53 per year) indicate the stock is lightly exploited in the northern part of the fishery. For example, using Lucas' (1974) estimate of *M* of 0.2 per month or 2.4 per year, the range in *F* values equate to about 10-20% of *M*. As the exploitation rate $E = F/Z = F/(M+F)$ (Sparre and Venema 1998), *E* ranges from 0.10–0.18, well below 0.5 which is generally considered to represent a fully exploited stock.

At these low fishing mortality rates, both yield and value tend to remain relatively 'flat' over a broad range of sizes and ages at first capture (Figure 18-6 and Figure 18-9). Under such low *F* scenarios, the benefits of closures, in terms of increasing yield and value, are diminished. The results are consistent with closures having little positive effect when stocks are subjected to low fishing mortality. Under low *F* it does the size or age at first capture is largely irrelevant.

The benefits of regulating the size or age at first capture, through spatial closures, becomes greater and more apparent under high fishing mortalities. To this end, the results indicate that yield and value per recruit could be increased by increasing *F*, which could be achieved by increasing effort in the region. This need not subject the stock to unacceptable risk. For example, the exploitation rate *E* could probably be increased from the estimated low values of 0.10–0.18 to 0.5, without significantly increasing the risk of overfishing.

It should be noted that the current low estimates of *F* were derived from a relatively localised (i.e., 22°-24°S) tag-release experiment and so they should not be considered representative of the whole fishery. Furthermore, the estimates of *F* should be considered with caution because the choice of months to include or exclude, and the duration of the periods used, can have a significant effect on the estimate of *Z*, and subsequently *F*. We chose two periods (six months May 2009 to October 2009, and 13 months May 2009 to June 2010), both of which resulted in low *F* values.

18.5.1 Will closing the area increase yield or value?

The yield and value per recruit results need to be examined in relation to the sizes and ages of the prawns in the different areas (Figure 18-3), particularly the proposed closure. Within the proposed closed area, males and females were mostly 0.5–1.0 years old. As Figure 18-5 and Figure 18-6 indicate, yield generally peaks at ages at first capture of 0.3–0.7 years, closing the area would likely result in an increase in age at first capture and a subsequent reduction in yield.

Given the range of ages of prawns inside the closure, value per recruit for both males and females falls within, or is close to, the maximum attainable value for a broad range in F (i.e., 0.27, 0.42 and 2.40 per year). If the area was closed, the increased ages at first capture would probably more-closely reflect those of the mid area in Figure 18-3, which is the closest area adjacent to the closure. As a result, the ages at which the prawns are harvested in the area would increase to about 0.75–1.25 years (i.e., 8–15 months) which would result in a decline in harvest value.

Therefore, given that both yield and value of the catch would likely decline if the area was closed, we recommend that the closure not be implemented. As the value per recruit is influenced by the wharfside price, any significant change in prices may justify a re-assessment of the analysis. However, yield per recruit is not affected by price and therefore the findings pertaining to yield are unlikely to change in future.

19 Appendix 7. Fishing power and standardised catch rates: Implications of missing vessel-characteristic data from the Australian eastern king prawn fishery

J. M. Braccini[1], M. F. O'Neill[2], A. B. Campbell[1], G. M. Leigh[1], and A. J. Courtney[1]

[1]Agri-Science Queensland, Department of Employment, Economic Development and Innovation, Ecosciences Precinct, GPO Box 267, Brisbane, Queensland, 4001, Australia.
[2]Agri-Science Queensland, Department of Employment, Economic Development and Innovation, Maroochy Research Station, PO Box 5083 SCMC, Nambour, Queensland, 4560, Australia; e-mail: michael.o'neill@deedi.qld.gov.au

19.1 Abstract

Standardised time series of fishery catch rates require collations of fishing power data on vessel characteristics. Linear mixed models were used to quantify fishing power trends and study the effect of missing data encountered when relying on commercial logbooks. For this, Australian eastern king prawn (*Melicertus plebejus*) harvests were analysed with historical (from vessel surveys) and current (from commercial logbooks) vessel data. Between 1989 and 2010, fishing power increased up to 76%. To date, both forward-filling and, alternatively, omitting records with missing vessel information from commercial logbooks produce broadly similar fishing power increases and standardised catch rates, due to the strong influence of years with complete vessel data (16 out of 23 years of data). However, if gaps in vessel information had not originated randomly and skippers from the most efficient vessels were the most diligent at filling in logbooks, considerable errors would be introduced. Also, the buffering effect of complete years would be short lived as years with missing data accumulate. Given ongoing changes in fleet profile with high-catching vessels fishing proportionately more of the fleet's effort, compliance with logbook completion, or alternatively ongoing vessel gear surveys, is required for generating accurate estimates of fishing power and standardised catch rates.

Keywords: data imputation; fishing logbook compliance; trawl fishery; fisheries management

19.2 INTRODUCTION

Catch and fishing-effort statistics are widely used as basic inputs for assessment and management of marine resources (Beverton and Holt 1957). Stock assessment models are commonly tuned to time series of assumed relative abundance. Tuning to raw, unstandardised fishery catch rates based on nominal effort such as fishing days or hours fished can lead to errors in stock assessment and to management decisions that fail to meet harvest objectives (Hilborn and Walters 1992; Kimura 1981; Mahévas *et al.* 2004; O'Neill and Leigh 2007; Robins *et al.* 1998). Management decisions should instead be based on standardised fishing effort and catch rates as these provide a more accurate representation of changes in abundance and fishing mortality (Cunningham and Whitmarsh 1980). The effective fishing effort of a fleet is a function of its fishing efficiency, which generally increases in time due to the continuous technological development and tactical adaptation shown by commercial fishers (Goñi *et al.* 1999; O'Neill and Leigh 2007; Robins *et al.* 1998). Hence, inferences on trends in abundance made from trends in catch rates are misleading if the effects of changes in the profile of fishing fleets, improvements in fishing technology, changes in management regulations, and the biology and abundance of the species are not separated (Bishop *et al.* 2004).

Relative fishing efficiency, or fishing power, is a measure of the efficiency of an average vessel at catching a species. To quantify changes in fishing power, information on the components of fishing effort, i.e., the skills and knowledge of the skipper and crew, fishing capacity and fishing activity, is required (Marchal *et al.* 2007). Fishing capacity is a function of a vessel's physical attributes, gear technology and on-board equipment, whereas fishing activity is a function of the duration of a fishing trip and other factors such as the number and size of gear deployed and the effective fishing time (Marchal *et al.* 2007). Quantifying changes in fishing power is typically done by incorporating information on temporal changes in vessel characteristics considered to influence fishing efficiency into linear and non-linear models (see Maunder and Punt 2004). Information on vessel characteristics is commonly obtained from purposely-designed surveys (Marchal *et al.* 2007; O'Neill and Leigh 2007) or commercial logbooks (Horn 2003; Mahévas *et al.* 2004).

All variables influencing fishing power should be included in the analysis (Kimura 1981). In practice, including all these variables is difficult for reasons ranging from high costs of acquiring data, especially retrospectively, to lack of contrast among vessels in fisheries with small fishing fleets (Bishop *et al.* 2004). The latter authors fit a range of statistical models to different scenarios of available information on vessel characteristics of the Australian Northern Prawn Fishery. In the absence of vessel information, the analyses were unable to separate trends in prawn abundance from trends in fishing power, leading to errors in both. Hence, for complex fisheries such as prawn fisheries, where technological developments, changes in fleet composition and input control management were common, detailed information on vessel characteristics is needed (Bishop *et al.* 2004). Prawn fisheries therefore provide a good case study of the influence of vessel information quality on fishing power and abundance trend estimates. We explored the effects of combining historical (obtained from vessel surveys) with current but incomplete logbook vessel information on the estimation of fishing power and standardised catch rates of the eastern king prawn (*Melicertus plebejus*, EKP).

The EKP fishery is the most valuable fishery in Queensland, Australia. It forms part of the Queensland east coast otter trawl fishery (ECOTF) in which 9000 tonnes of catch are marketed annually at a value of AU$ 101–109 million (Kerrigan *et al.* 2004). Its 480 vessel licences registered in 2007 (Courtney *et al.* 2008) also make the ECOTF the largest trawl fleet in Australia in terms of vessel numbers (O'Neill and Leigh 2007). Within the ECOTF, the EKP fishery is the most important in terms of landings with about 2500 tonnes being reported annually.

Between 1989 and 2004, the relative fishing power of the EKP fishery increased by up to 51% due to changes in the fleet profile and continual upgrades of vessel characteristics (O'Neill and Leigh 2007). In addition to the increase in fishing power, there was concern about high levels of fishing effort, partly due to high fuel prices making it less attractive for fishers to target other prawn species in more remote fishing grounds (e.g., tiger and endeavour prawns off northern Queensland), and to buoyant prices commanded by EKP. Therefore, quantifying the current increase in the fishing power of the EKP fishery was needed to understand the extent of current effective effort and fishing mortality, and to allow estimation of a reliable relative index of abundance for stock assessment.

Information on the characteristics of vessels participating in the EKP fishery was available from January 1988 to May 2004 from two surveys of vessel owner/operators (O'Neill and Leigh 2006). From June 2004 onwards, vessel information was recorded in fishers' compulsory daily logbooks. However, as for many other fisheries in Australia (Haywood and Die 1997) and elsewhere (Lugten 2009), a large proportion of logbook records were incomplete. This was a management concern: what was the effect of incomplete vessel information on the estimation of fishing power and ultimately, the standardisation of catch rates? How do historical data (which have complete information for surveyed vessels) influence these estimates? Should management allocate more resources to improve the way skippers fill in the logbooks? The objectives of the present study were therefore to: 1) quantify the increase in the fishing power of the EKP trawl fishery from 1988 to 2010; and 2) evaluate the effects of missing vessel data on the estimation of fishing power and standardised catch rates.

19.3 MATERIALS AND METHODS

19.3.1 Data

Catch, effort and vessel-characteristic data were sourced from the Queensland commercial compulsory logbook system from January 1988 to May 2010 and two face-to-face questionnaire surveys of vessel owner/operators. The resolution of otter-trawl catch data was daily on half-degree spatial grid. An October fishing closure was instituted in 2004, and no catch data were present since then. Catch data were present for all other months in all grid squares analysed.

From 1988 to May 2004, the logbook system contained no vessel data so this information was obtained from two purposely-designed surveys of vessel owner/operators conducted by O'Neill and Leigh (2006). From June 2004 to May 2010, information on vessel characteristics was reported in logbooks, but these had a large percentage of incomplete data. All available vessel data were linked to the daily logbook catch and effort records.

The vessel data included engine rated power, gear box ratio, average trawl speed, fuel capacity, fuel consumption per night, propeller size, presence or absence of a propeller nozzle, global positioning system, plotters, computer mapping, sonar and colour sounder, use of try-gear, type and use of by-catch reduction devices (BRD) and turtle exclusion devices (TED), number of nets (single, double, triple, quad or five nets), total net head rope length combined for all nets, net mesh size, type of ground chain (fixed drop chains, drop chain with sliding rings, drop rope and chain combined, looped chain or other less common configurations), chain size, and type of otter board (Bison, flat, Kilfoil, Louvre or other less common types).

19.3.2 Imputation of missing vessel data

Missing vessel information from June 2004 to May 2010 was imputed in two different ways, either to omit the empty records from analysis (Data set 1, D1) or to forward-fill all missing vessel records (Data set 2, D2). The approach used to forward-fill missing data assumed that a skipper recorded only new vessel data when there was a change in any of the vessel or gear variables (referred as the ‘continuity’ assumption). Therefore, D2 was first sorted by date and, for each vessel owner/operator, gaps were filled using the value of the last record with available information until another record with information was available, which was then used to fill subsequent empty records. For the fields ‘presence of global positioning system’, ‘presence of computer mapping software’, and ‘presence of bycatch reduction devices and turtle excluders’, all records with missing information were assumed to carry these devices based on trends reported by O'Neill and Leigh (O'Neill and Leigh 2006) and current legislation.

The above method of forward-filling is well known in the literature on the analysis of longitudinal data (i.e., data collected over time on the same experimental subjects), where it is known as ‘last observation carried forward’ (LOCF). Once a subject drops out of the study, the last recorded data on that subject are carried through to the endpoint of the study. In the context of drop-outs of subjects in clinical trials, this method has been heavily criticised for introducing biases in the results (e.g., Siddiqui *et al*., 2009; Gibbons *et al*., 2010).

The context of commercial fisheries is somewhat different. There are no true ‘drop-outs’ because reporting of gear and vessel characteristics is compulsory and licensed fishers can always be reminded to fill in their log sheets. Also, the LOCF assumption may be close to the truth if fishers see no point in completing the equipment log sheet when nothing has changed, but make the effort to update their logs when a purchase of new gear jogs them to think of it. Vessel characteristic data change infrequently and in discrete jumps, unlike many variables in clinical trials.

Fishers who leave the fishery are not classical drop-outs, because it is correct not to include them after they leave. For example, if inefficient fishers leave, the fishing power of the fleet, measured as overall catch per unit effort at a standard level of abundance, will increase. The statistical analysis will correctly show this.

19.3.3 Statistical analysis of catch data

All data were analysed by vessel codes that identified the combination of vessel hull and owner. To be consistent with current stock assessments (O'Neill *et al.* 2005), analyses relate only to EKP recruited to offshore fisheries (not juveniles within bays or estuaries). To match the cycle of fishing and recruitment, fishing year was defined to start in November and end in October (O'Neill *et al.* 2005). Estimates for the 2010 fishing year were based only on the months up to May. Annual trends in fishing power were calculated for two management sectors: waters ≤ 50 fathoms deep (shallow water sector) and waters > 50 fathoms deep (deep water sector).

Linear mixed models were applied using the method of residual maximum likelihood (REML) assuming normally distributed errors on the log scale (O'Neill and Leigh 2006; 2007). The response variable was a vessel's natural logarithm transformed daily harvest (kg). The model included fixed and random terms. The fixed terms were for fishing year, month, spatial grid square, depth sector, lunar cycle, hours fished, and the vessel's gear characteristics. Individual vessels were treated as random terms. The statistical software package GenStat (GenStat 2011) was used for the analysis and provided asymptotic standard errors for all estimates. Any influential correlations of parameter estimators were assessed, and terms were dropped from the analysis if necessary. The importance of individual fixed terms was assessed using F statistics, calculated by dropping individual terms from the full fixed model. Data from shallow-water grid squares were given a higher weighting than deep-water squares in order to compensate for the exclusion of many predominantly shallow squares from the analysis. The area of the fishery covers approximately 55% deep water and 45% shallow, whereas the model contained 71% deep-water grid squares and only 29% shallow. Grid squares containing both deep and shallow water had to be excluded because it was uncertain whether deep-water or shallow-water fishing gear was used. The data weighting corrected for the fact that the squares excluded from the model contained mainly shallow water, with only a little deep water. For each depth sector, grids were ordered by total catch and those grids where 95% of the catch was taken were selected. Alternative models were tried and the final model was selected based on comparing deviance statistics, the proportion of explained variance, and the significance of each explanatory variate. Definition of the final model used was as follows:

$$\log_e\left(C_{ivayml}\right) = \beta_0 + \mathbf{X}\boldsymbol{\alpha} + \mathbf{Z}\boldsymbol{\gamma} + \varepsilon \qquad (1)$$

where C_{ivayml} was the catch taken on day i by the vth vessel in grid a, during fishing year y, month m and lunar cycle l; parameter β_0 was a scalar intercept; $\boldsymbol{\alpha}$ a matrix of fixed parameter terms including $\boldsymbol{\beta}_1$, $\boldsymbol{\beta}_2$, $\boldsymbol{\beta}_3$ and $\boldsymbol{\beta}_4$, multiplied by data $\mathbf{X}$ ($\mathbf{X_1}$, $\mathbf{X_2}$, $\mathbf{X_3}$ and $\mathbf{X_4}$); $\boldsymbol{\gamma}$ a vector of random vessel terms with data $\mathbf{Z}$; ε the normal error term. Vectors $\boldsymbol{\beta}_1$, $\boldsymbol{\beta}_2$, $\boldsymbol{\beta}_3$ and $\boldsymbol{\beta}_4$ were parameters for abundance, catchability, lunar phase, and hours fished respectively. The abundance vector $\boldsymbol{\beta}_1$ included terms for the two-way interactions of fishing year, month, and grid square. The catchability vector $\boldsymbol{\beta}_2$ included parameters for vessel characteristics (engine rated power, propeller nozzle, otter trawl board type, bycatch reduction devices and turtle excluders, trawl ground gear type, and the use of try gear net), navigation equipment (Global Positioning System), and trawl net configuration (net type, mesh size, and the interaction of net length with depth sector) some of which were categorical and others continuous. The vector $\boldsymbol{\beta}_3$ consisted of a parameter term for lunar luminance and one for lunar luminance advanced seven days (1/4 phase), and their interaction with depth sector. Natural logarithm transformations were applied to continuous $\mathbf{X}_2$ and $\mathbf{X}_4$ variate data.

19.3.4 Fishing power

Following O'Neill and Leigh (2006; 2007), relative fishing power was calculated as a proportional change in average catch rates from fishing year to fishing year under constant abundance conditions. The expected catch on each day fished by each vessel was calculated as

$$\mathbf{c} = \exp\left(\beta_0 + \mathbf{X}\boldsymbol{\alpha} + \mathbf{Z}\boldsymbol{\gamma}\right) \qquad (2)$$

where $\mathbf{c}$ was the vector of expected catch for each vessel and day fished and $\mathbf{X}$, $\boldsymbol{\alpha}$, $\boldsymbol{\gamma}$ and $\mathbf{Z}$ are as in Eq. (1). Within $\mathbf{X}\boldsymbol{\alpha}$ the terms represented by $\mathbf{X}\boldsymbol{\beta}_1$ were held constant to provide standard conditions of abundance, enabling predictions of change in fishing power. Thus, for each data record in the model, the expected catch and hence the contribution of that record to relative fishing power were determined by the value of the corresponding element in $\mathbf{X}_2\boldsymbol{\beta}_2 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\boldsymbol{\beta}_4 + \mathbf{Z}\boldsymbol{\gamma}$. The model contained no interactions of abundance $\boldsymbol{\beta}_1$ with other model terms. Therefore, any standard conditions of abundance may be chosen, and the complexity of missing months (October for years > 2003) in $\boldsymbol{\beta}_1$ was avoided.

For each fishing year, an average catch $\bar{c}$ was defined as the arithmetic mean of elements of **c** that were within the year. Fishing power was then defined as

$$\mathbf{f}_\mathbf{y} = \frac{\bar{\mathbf{c}}}{\bar{c}_{1989}}$$

where $\mathbf{f}_\mathbf{y}$ was the vector of proportional change in expected catch relative to 1989 and $\bar{\mathbf{c}}$ was the vector of annual average catches under standard conditions. The 1989 fishing year was selected as the base reference because it was the first fishing year with complete catch records.

To judge the effect of changes in fleet composition, a version of fishing power was also calculated from the fixed terms $\mathbf{X}_2\boldsymbol{\beta}_2 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\boldsymbol{\beta}_4$ only. This calculation excluded the random vessel term $\mathbf{Z}\boldsymbol{\gamma}$. The comparison to the full change in fishing power, which included both fixed and random terms, shows the degree to which the tendency of inefficient boats to exit the fishery and efficient boats to remain has affected the overall fishing power of the fleet.

Fishing power was also calculated for deep water and shallow water separately, by restricting the averaging of $\mathbf{X}_2\boldsymbol{\beta}_2 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\boldsymbol{\beta}_4 + \mathbf{Z}\boldsymbol{\gamma}$ or $\mathbf{X}_2\boldsymbol{\beta}_2 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\boldsymbol{\beta}_4$ to catch records from deep-water and shallow-water grid squares respectively.

Confidence intervals on fishing power estimates were generated by 1000 Monte Carlo simulations (O'Neill and Leigh 2006). The variations in fixed parameters were calculated using the parameter estimates and their covariance matrix to construct a multivariate normal distribution of values. Realisations of the random vessel effects were calculated from normal distributions based on the means and standard deviations for vessels fishing in each fishing year, month and grid. Calculated 2.5 and 97.5% percentiles on the fishing power distributions represented 95% confidence intervals.

19.3.5 Standardised catch rates

Standardised catch rates were given by the values of the $\boldsymbol{\beta}_1$ parameters, which provided an abundance estimate in each year, month and grid square, with two-way interactions. The calculation of annual standardised catch rates for the fishery (1988–2003) involved averaging over month and grid square and their two-way interactions with each other and with year. This averaging was done on the log scale, weighting all months and grid squares equally, using the GenStat procedure “vpredict”. No missing month or grid terms were present in $\boldsymbol{\beta}_1$ prior to 2004.

19.3.6 Sensitivity analyses

Analyses were conducted to determine the effect of missing vessel data on relative fishing power and standardised catch rates. Given that the fishing years 1988–2003 constitute a baseline upon which the effects of gaps in data can be explored, a data set was created including only these records. This data set had complete information on vessel characteristics for the surveyed vessels (base case). Two aspects of these data were then examined: 1) how is accuracy of fishing power estimates affected by the way gaps in vessel data originate? and 2) how many years with missing vessel information does it take before errors in fishing power become unacceptable?

The process causing missing values in the vessel characteristic fields of logbooks was unknown. Therefore, two hypothetical cases for comparison with the base case were explored (Table 19-1). At one extreme, gaps in vessel data originated randomly (referred as the 'random' assumption), i.e., any given skipper decided to fill in or not fill in the vessel data at random (this was considered the best-case scenario). At the other extreme, only the best skippers (i.e., those with the top 30% random terms) fill in all the vessel data fields (this was considered the worst-case scenario, and is referred as the 'top vessels' assumption). REML was fitted to these data subsets to estimate model coefficients, calculate trends in relative fishing power and standardised catch rates, and compare with the base case.

Table 19-1. Description of sensitivity analyses and the data sets used.

Analysis effect	Scenario labels	Data sets
Imputing missing vessel information	Base case	Data set including all records for the period 1988–2003.
	Best case	Random sample of the base case (45% of records, corresponding to the percentage of filled in records for the period June 2004–2010).
	Worse case	Sample of the base case including only the records of the top catching vessels (assumed to be the vessels with the top 30% random fishing power coefficients, obtained from fitting the REML model to the base case).
Number of years with complete vessel information	Base case	As above.
	Top vessels 1	Complete records between 1988 and 2002. For 2003, complete records for 'top vessels' and incomplete records for the remaining vessels, which were forward-filled.
	Top vessels 2	Complete records between 1988 and 1997. For 1998–2003, complete records for 'top vessels' and incomplete records for the remaining vessels, which were forward-filled.
	Top vessels 3	Complete records between 1988 and 1992. For 1993–2003, complete records for 'top vessels' and incomplete records for the remaining vessels, which were forward-filled.
	Top vessels 4	Complete records between 1988 and 1999. For 1990–2003, complete records for 'top vessels' and incomplete records for the remaining vessels, which were forward-filled.

To explore sensitivities to the numbers of years with complete vessel information, four data subsets were created using the base case 1988–2003 data. The data subsets contained different numbers of years with complete and incomplete vessel information (Table 19-1). For the incomplete years, records from the 'top vessels' were maintained and for the remaining records, all vessel-characteristic information was removed and the gaps forward-filled as described above for the imputation of truly missing vessel data. Slightly different REML models, with individual vessels as random terms, were fitted to each of these data subsets to estimate model coefficients, calculate trends in relative fishing power and standardised catch rates, and were compared with the base case. Different models had to be used because some of the main terms and interactions were not significant or had insufficient observations when restricting the time series to 1988–2003.

19.4 RESULTS

19.4.1 Logbooks with complete vessel data were few

The total number of vessels participating in the EKP fishery declined from a peak of 407 vessels in 1991 to 153 vessels in 2010 (Figure 19-1). Complete vessel data were available from surveys covering the years between 1988 and 2003. No vessel information was available for non-surveyed vessels during this period. From June 2004 to May 2010, logbook records had a large percentage of missing vessel data. Overall, 60% of logbook records had at least some of the vessel or gear information fields filled in, ranging from 25% filled in for vessel fuel use to 62% filled in for engine rated power (Table 19-2). For the selected data analysed through linear mixed models, the percentage of logbook records with complete vessel data varied from 36 to 75% for D1 and from 86 to 92% for D2 per annum.

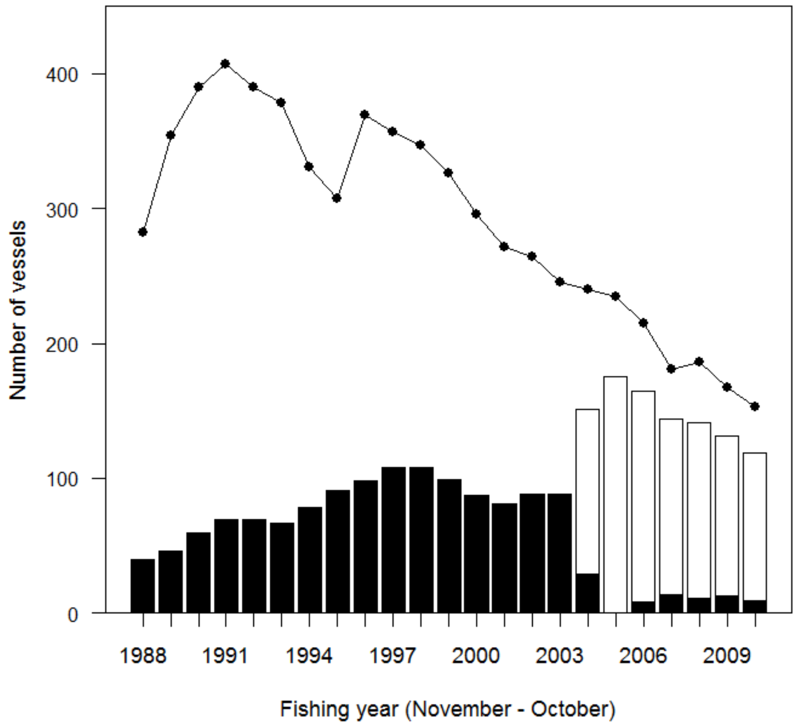


Figure 19-1. Total annual number of active vessels in the EKP fishery (line and points) and those with complete (black bar) and incomplete (white bar) vessel information. Vessel information was obtained from surveys between 1988 and 2003, and from commercial logbooks between 2004 and 2010. The number of vessel with no information is the difference between the total number of vessels and those with complete and incomplete information.

Table 19-2. Percentage of logbook records with vessel data from June 2004 to May 2010 (n=60,345).

Variable	Percentage filled in
Vessel length	61
Engine rated power	62
Trawl speed	46
Gear box ratio	60
Vessel fuel capacity	59
Vessel fuel use	25
Propeller diameter	56
Propeller pitch	41
Propeller nozzle	62
Sonar	62
Global positioning system	39
Computer mapping software	39
Try gear net	62
Bycatch reduction devices and turtle excluders	39
Mesh size	52
Ground chain gauge	61
Otter trawl board size	55
Net headrope length	55
Otter boards	60
Ground gear – chain size	28
Trawl gear – number of nets	61

Between 1988 and 2010, most of the vessel characteristics increased through time, while the average total net head rope length remained restricted by legislation (Figure 19-2). Standard drop chains and their variants were the most popular ground gear type. Flat otter boards were by far the most popular otter board type. Triple gear nets were by far the most popular net type, followed by recent adoptions of quad gear nets.

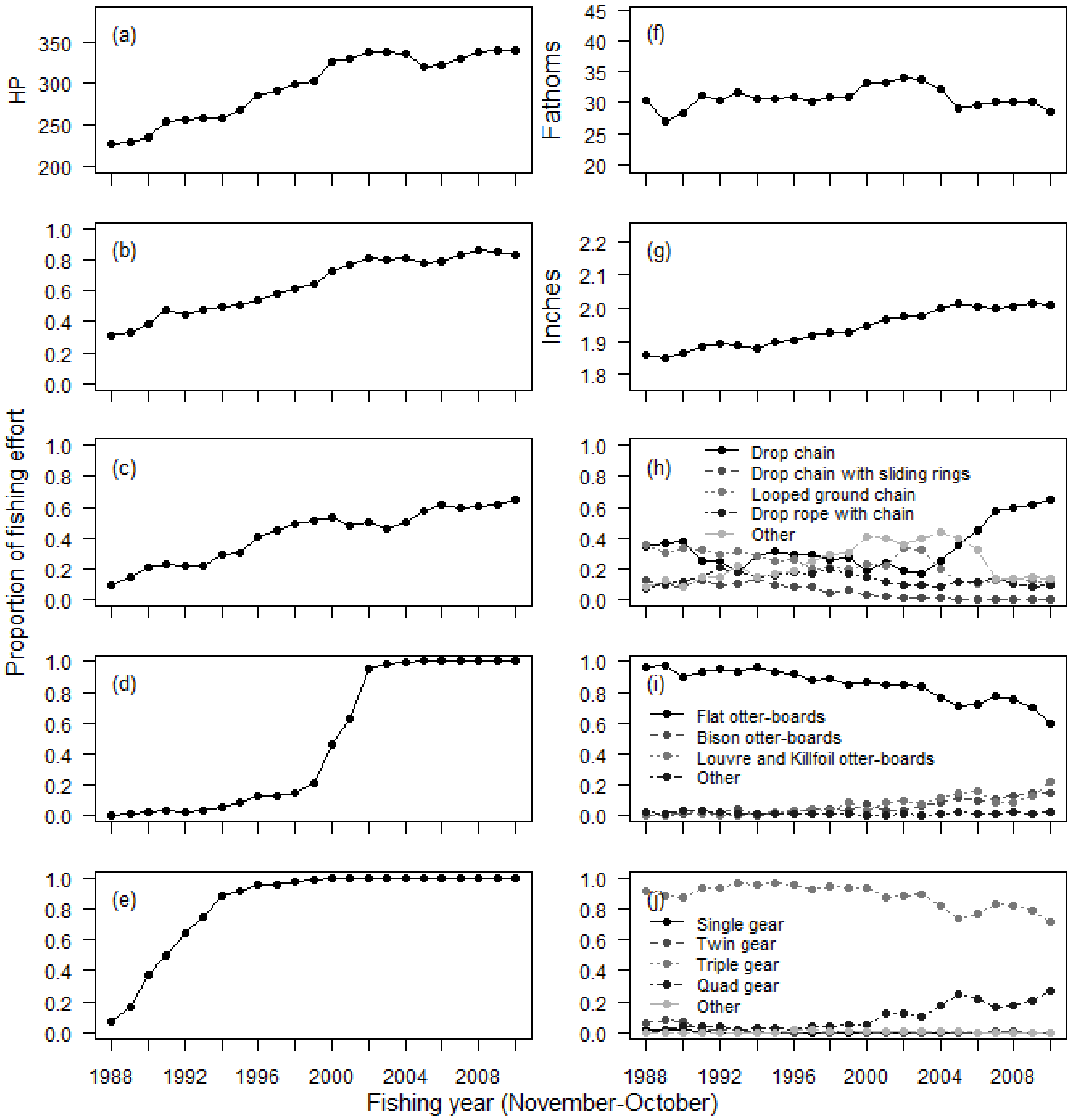


Figure 19-2. The EKP fleet's average and proportional use of (a) engine rated power, (b) propeller nozzle, (c) try gear net, (d) bycatch reduction devices and turtle excluders, (e) global positioning systems, (f) total net head rope length, (g) net mesh size, (h) ground gear, (i) otter boards, and (j) number of trawl nets. Summary statistics were based on the number of days fished by each vessel in each fishing year.

19.4.2 Ignoring or filling missing data produced similar estimates

There were correlations among vessel and trawl-net variates, so it was not possible to accurately measure their individual effects. Engine rated power (HP) was therefore assessed as the best surrogate of vessel length, gear box ratio, fuel capacity, fuel use, otter trawl board size, propeller pitch and propeller diameter. No other correlations between gear and technology variables were present.

The REML analysis showed that the abundance β_1, fishing power β_2, lunar phase β_3 and hours fished β_4 terms were highly significant for both D1 and D2 data sets (Table 19-3). The variance component for the random vessel terms was 0.2758 for D1 and 0.3184 for D2, equivalent to a coefficient of variation of 52.5% (=$0.2758^{½}$) and 56.4% (=$0.3184^{½}$), respectively, thereby accounting for a large part of the variation in vessel's annual EKP catches. Analysis of residuals supported the use of the normal residual distribution on the log scale.

Table 19-3. Summary of analyses and parameter estimates for catchability (fishing power $\boldsymbol{\beta}_2$) terms from the REML model (natural log transformed) fit to data sets D1 and D2.

	D1		D2	
Summary of analysis				
Fishing power β_2 d.f., deviance ratio	19, 39.1411		19, 40.8105	
Remaining terms d.f., deviance ratio	706, 39.9372		707, 50.9429	
	Value	**SE**	**Value**	**SE**
Residual variance	0.3010	0.0013	0.2970	0.0012
Variance component	0.2758	0.0241	0.3184	0.0261
Parameter estimates				
Engine rated power	0.1048	0.0218	0.0702	0.0190
Propeller nozzle	-0.0461	0.0104	-0.0308	0.0093
Global positioning system	-0.0494	0.0117	-0.0545	0.0114
Number of trawl nets				
Single	0.0000	0.0000	0.0000	0.0000
Double	-0.5013	0.0539	-0.4913	0.0523
Triple	-0.4339	0.0481	-0.4490	0.0472
Quad	-0.4063	0.0504	-0.4265	0.0489
Five	-0.2476	0.0562	-0.2397	0.0547
Net size				
Shallow	0.0806	0.0189	0.0551	0.0147
Deep	0.1899	0.0177	0.1803	0.0138
Mesh size	-0.4577	0.0452	-0.4389	0.0406
Ground gear				
Drop chain	0.0000	0.0000	0.0000	0.0000
Drop chain with sliding rings	0.0142	0.0250	0.0047	0.0237
Looped chain	-0.0151	0.0101	-0.0294	0.0083
Drop rope with chain	-0.0341	0.0113	-0.0229	0.0099
Other types	-0.0857	0.0103	-0.0397	0.0077
Otter boards				
Standard flat	0.0000	0.0000	0.0000	0.0000
Bison	-0.0049	0.0180	-0.0045	0.0134
Louvre and Kilfoil	0.0237	0.0142	0.0366	0.0125
Other types	0.1045	0.0261	0.0324	0.0210
BRD and TED	0.1325	0.0096	0.1437	0.0094
Net–try gear	-0.0229	0.0082	-0.0360	0.0070
Effort hours	0.0621	0.0021	0.0741	0.0021

The estimated gear and technology parameters obtained from fitting the REML model to either D1 or D2 were similar (Table 19-3). Higher engine power was associated with higher EKP catches. Vessels installed with propeller nozzles or GPS were associated with having 4 and 5% lower average catches, respectively. Vessels using quad gear achieved between 2 and 3% (D2 and D1, respectively) larger average catches than vessels fishing with triple gear. In shallow and deep waters, larger average catches were associated with larger nets and smaller mesh sizes. Vessels using drop chain ground gear achieved larger than average catches. Vessels using Louvre and Kilfoil otter boards achieved between 3 and 4% (D1 and D2, respectively) larger average catches than vessels fishing with Bison otter boards. Vessels using BRDs and TEDs achieved between 14 and 16% (D1 and D2, respectively) larger than average catches. Vessels using try nets achieved between 2 and 4% (D1 and D2, respectively) smaller average catches. Vessels fishing longer hours achieved larger average catches.

19.4.3 Fishing power increases

Analysis of data sets D1 and D2 produced broadly similar trends in average relative fishing power (Figure 19-3). Between 1989 and 2010, fishing power increased between 76 and 69% in shallow waters, between 22 and 25% in deep waters, and between 48 and 55% across both management components (D1 and D2, respectively). Uncertainty in fishing power estimates was higher in shallow waters due to higher variability in vessel characteristics in this depth sector. Changes in fishing power due to vessel upgrades were measured by the $\boldsymbol{\beta}_2$ fixed effects (grey lines Figure 19-3) whereas changes due to evolution of the fleet profile were measured through the random vessel terms $\boldsymbol{\gamma}$. The random term effect was illustrated by the difference between the overall fishing power estimate (black line) and the fishing power estimate from the $\boldsymbol{\beta}_2$ fixed effects only (grey line). Note that fishing power estimates for 2010 were based only on the months up to May. Increases in fishing power were mostly driven by the changing fleet profile (random term). Higher engine rated power and the use of BRDs and TEDs, and to a lesser extent, quad net gear, drop chains and their variants, and Louvre and Kilfoil otter boards, also contributed to the increased fishing power.

The similar trends from data sets D1 and D2 appear to be due to the strong influence of years with complete vessel information (period 1988–2003). However, if more years of missing data occur into the future, the trends can be expected to diverge, and the errors can be expected to increase when gaps are not forward-filled (see simulations below). Although fishing power trends based on D1 and D2 showed overlapping confidence intervals, the fishing power trends for depth combined started to diverge in 2000 and showed the largest divergence in 2006 due to the somewhat different fleet composition. The differences in fleet composition resulted from the forward-filling or discarding of missing vessel information.

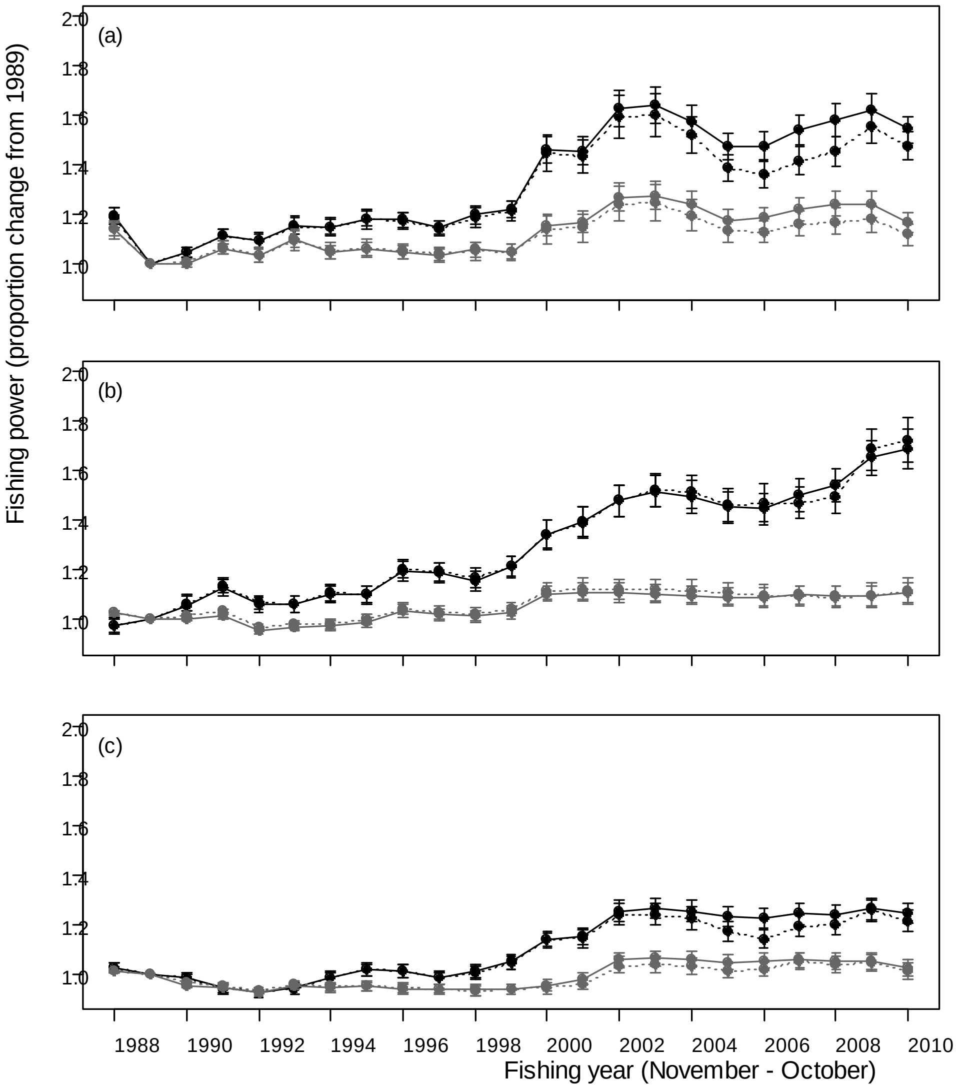


Figure 19-3. Comparison of fixed and random effects (with 95% confidence intervals) on the proportional change in fishing power from 1988 to 2010 for (*a*) depths combined, (*b*) shallow water (≤ 50 fathoms), and (*c*) deep water (> 50 fathoms) based on data set D1 (dotted line) and D2 (solid line). Total terms (i.e., fixed and random) are shown in black and fixed terms only are shown in grey. The proportional change represents the differences from the reference year 1989, set to 1.

19.4.4 Effects of missing vessel data

The assumption that gaps in logbooks were generated randomly yielded no differences in trends of relative fishing power and very similar trends in relative abundance (Figure 19-4). Different trends in fishing power and relative abundance were obtained from assuming that only the skippers from the most efficient vessels filled in the logbooks.

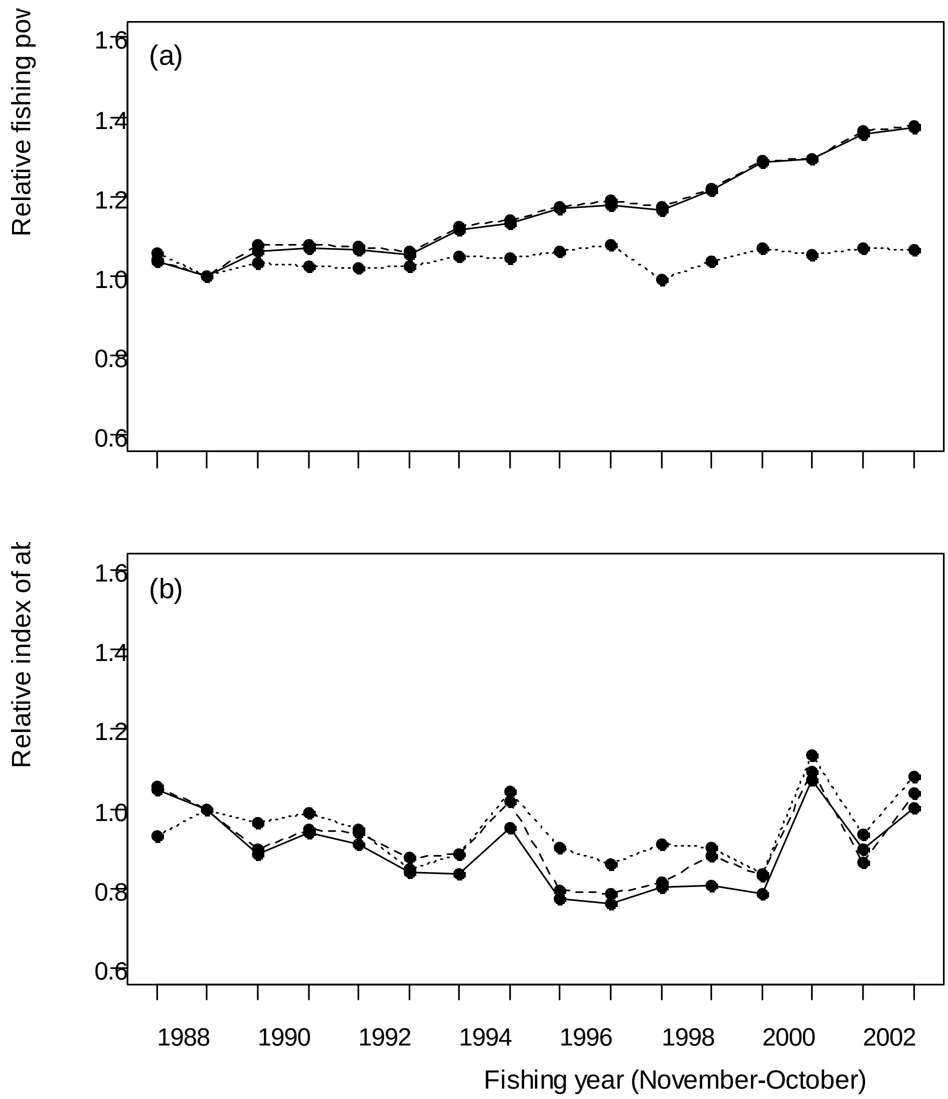


Figure 19-4. Sensitivity analyses on (a) relative fishing powers and (b) standardised catch rates between 1988 and 2003. Base case (solid line) included all 1988–2003 data; random subset (broken line) assumed a random sample of 1988–2003 data; top-vessels subset (dotted line) assumed a sample of 1988–2003 data from only top vessels.

Fishing power estimates were sensitive to the number of years with complete vessel information (Figure 19-5). For the data subsets (except for 'top vessels 1' which has only one incomplete year), the fishing power in the years with forward-filled incomplete vessel information gradually declined relative to 'base case' given that vessel upgrades were not taken into account. Relative abundance estimates showed different sensitivities to the number of years with complete vessel information. Estimates based on data subsets 'top vessels 1' showed almost identical trends to 'base case'. However, differences from 'base case' increased as years with complete vessel information decreased.

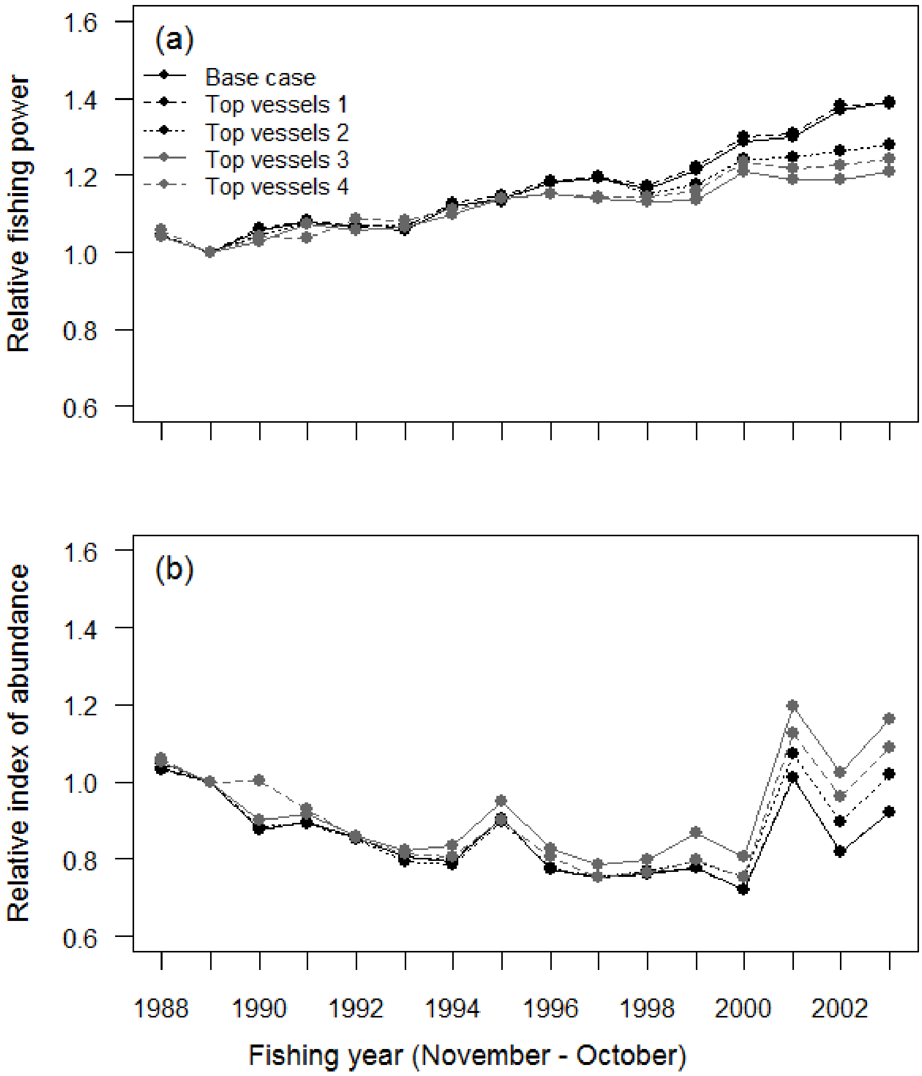


Figure 19-5. Sensitivity of (*a*) relative fishing power and (*b*) standardised catch rate estimates to different numbers of years with complete vessel information. Base case = 1988–2003 data; top vessels 1 = complete records between 1988 and 2002; top vessels 2 = complete records between 1988 and 1997; top vessels 3 =complete records between 1988 and 1992; top vessels 4 =complete records between 1988 and 1989.

19.5 Discussion

Measuring effective effort is fundamental for stock assessment for fisheries managed through effort limiting controls, such as prawn fisheries, as every increase in fishing power results in nominal and effective effort diverging (Cunningham and Whitmarsh 1980; Hilborn and Walters 1992; Kimura 1981; Rothschild 1972). Due to the high sensitivity of management quantities to the rate of increase in fishing power (O'Neill *et al.* 2005; Wang and Die 1996), accurate fishing power estimates are required for achieving effective management strategies. The present study showed how the use of incomplete vessel information obtained from commercial logbooks can generate erroneous estimates of fishing power and standardised catch rates (based on the ‘top vessels’ assumption). These findings inform management on the need to reinforce the regular completion of commercial logbooks.

19.5.1 Fishing power increases

Fishing power in the EKP fishery increased substantially (> 69% increase in shallow waters) between 1988 and 2010. Annual changes were driven by changes in the fleet profile, particularly from 1999 onwards, where less efficient vessels exited the fishery or reduced the numbers of fishing days and the more efficient vessels remained. Upgrades to vessel engine power and adoption of BRDs and TEDs were also influential but to a lesser extent. Three of the negative model terms (GPS, propeller nozzle and number of trawl nets) seem counter-intuitive. However, analyses based on fishery-dependent (observational) data can sometimes produce unexpected parameter estimates for the vessel gear terms due to low contrast in the data for these parameters with respect to the full model. Alternatively, this may represent the range/change of vessels fishing and the practical combination of certain gears and specific fishery behaviour. Negative estimates for the parameter GPS may be due to some unique features of EKP and the fishery. This species has a strong northerly migratory pattern in much greater depths than other prawn species and are generally fished along narrow depth contours (O'Neill and Leigh 2007). These features may have lowered the significance of GPS in this particular fishery, especially with high boat numbers indicating fishing areas for non-GPS boats in the late 1980’s and early 1990’s. The effect of propeller nozzles was marginally negative. Since 2004, larger tiger prawn (*Penaeus* spp.) vessels with nozzles have fished more nights for EKP. Eastern king prawns are fished at greater depths than tiger prawns and along straight depth contours rather than trawling around patches of ground/prawns. Given some change in the fleet vessels, the aspect of long trawl shots along depth contours may negate the benefit of propeller nozzles. Finally, the model prediction of higher catch rates for a single net was due to only one vessel early in the time series when prawn catches were higher. Irrespective of this, the model does predict the natural progression of higher catches from twin to five nets. In any case, analyses removing the GPS, propeller nozzle and number of trawl nets terms produced very similar (non-significantly different) results.

Using a slightly different model structure, O'Neill and Leigh (2007) reported a 51% increase in fishing power between 1989 and 2004 and forecasted future increases due to further upgrades in vessel characteristics, and continuous changes in fleet profile. Our findings confirmed these predictions; although in deep waters fishing power remained relatively stable since 2004, the shallow water sector experienced a continuous increase. This reflects the higher potential for the smaller, less efficient shallow-water vessels to increase their fishing power, compared to the larger, more powerful deep-water vessels. Further, the incorporation of updated information and new covariates for which information became available (e.g., hours fished, depth sector) into the mixed models showed a somewhat different pattern of fishing power increase. Therefore, future rates of increase in fishing power may not necessarily be extrapolated from current observed trends because new emerging technologies may be adopted in the future. This highlights the importance of maintaining the ongoing collection of vessel information for quantifying changes in fishing power and, hence, effective fishing effort.

19.5.2 Ignoring or filling missing data produced similar estimates

Based on the ‘continuity’ assumption (i.e., skippers record new vessel information when there is a change vessel or gear characteristics and all vessels carry GPS and mapping software), the decision as to whether forward-fill (D2) or omit (D1) records with missing vessel data has to date had a minor effect on the estimation of fishing power and standardisation of catch rates due to the strong influence of years with complete vessel information (period 1988–2003). The large sample size of the data sets (>100,000 records), particularly the complete records, hedged against the missing vessel data from commercial logbooks and the uncertainty about how to deal with those gaps. From a fisheries management perspective, the small influence of missing vessel data in recent years alleviated pressure on the organisations in charge of managing logbook programs as there seems to be no urgent need for allocating effort to improve logbook compliance. However, this is only expected in the short term. Not accounting for missing time–area observations can lead to biased estimates of standardised catch rates (Walters 2003), with simulation studies showing that filling in missing data considerably decreased bias (Carruthers *et al.* 2011; 2010). Our simulations showed that accuracy and precision of fishing power and standardised catch rate estimates decreased when gaps in vessel information were not filled in (see further discussion below). This illustrated the value of the historical information on vessel characteristics collected independently and before there was a mandatory requirement to record this information in logbooks.

Historical fisheries data have been invaluable for determining long-term population and ecosystem changes (Jackson *et al.* 2001; MacKenzie *et al.* 2002). Certainly for the EKP fishery, complete information on changes in vessel characteristics collected from past surveys has been very valuable for estimating trends in fishing power and standardised catch rates. However, if current gaps in the vessel information recorded in commercial logbooks are not addressed by a reinforcement of logbook reporting compliance, years with complete vessel information will be less influential as years with incomplete vessel information progressively accumulate. In that case, accuracy and precision in the estimation of fishing power and standardised catch rates is expected to decrease. Alternatively, if compliance with fishing logbooks could not be improved, more costly gear surveys should be reintroduced rather than applying gap-filling procedures (Walters 2003).

19.5.3 Effects of missing vessel data

Depending on how the gaps in vessel information of commercial logbooks originated, fishing power and standardised catch rate estimates can be considerably in error. If gaps originated randomly, estimates of fishing power and standardised catch rates would not be greatly affected. However, it is unlikely that missing vessel information originates randomly; there must be an underlying process causing these gaps. If the skippers from the less efficient vessels failed to fill in the vessel fields from commercial logbooks and only skippers from the most efficient vessels were the most diligent at filling in logbooks (i.e., the ‘top vessels’ assumption), considerable errors would be introduced in the estimation of fishing power and standardised catch rates. Based on this assumption, fishing power estimates were sensitive to the number of years with incomplete vessel information. All the simulated data series with six or more years with incomplete information showed a gradual departure from the base case. Relative abundance estimates were more robust and were substantially inaccurate only when five (i.e., 31% of data) or less years had complete vessel information. The sensitivity of fishing power and relative abundance estimates to available vessel information has been reported in other prawn fisheries. For example, for standardising fishing effort and building an abundance index in the Northern Prawn Fishery, detailed information on vessel characteristics is needed; otherwise, partial or no vessel information leads to confounded estimates (Bishop *et al.* 2004). An exploratory analysis of the relative efficiency of each vessel and the percentage of complete vessel information of each vessel yielded no clear patterns, which warrants more specific investigation. The ‘top vessels’ assumption probably constitutes a worse-case and overly simplistic scenario. Most likely, the process originating logbook gaps lies in between the ‘random’ and ‘top vessels’ extremes. In any case, understanding how gaps originate would not be relevant if logbook gaps in vessel information were minimised through better compliance in the first place.

It may be possible to undertake a more sophisticated analysis of these data using methodology from the literature on analysis of clinical trials, such as mixed-effect models for repeated measures (MMRM; see e.g. Siddiqui *et al*., 2009). However, compared to clinical trials, fisheries are much more affected by external events such as changes in management, input costs (e.g., fuel) and product prices. Regression models may struggle to model fishing vessels both before and after such an event. A direct transfer of clinical-trial methodology would be problematic.

19.5.4 Implications for management

For fisheries that rely mostly on commercial logbook data for input to stock assessments, standardisation accuracy is particularly important (Bishop *et al.* 2008). Currently, estimates of fishing power and standardised catch rates for EKP are based on 16 years of complete vessel information and only seven years with incomplete records. Hence, it is expected that these estimates will not be largely affected in the short term (based on the 'continuity' assumption) if compliance of logbook reporting is not immediately reinforced. However, this is only expected in the short term. In addition, our simulations assumed that the rate of future technological development of the fishery follows the 1988–2003 trends. If trends in vessel and gear characteristics increased, or new technologies were adopted, estimates of fishing power and standardised catch rates would become more sensitive to the number of years with missing information. Given that technological improvements are likely to continue occurring in most fisheries (O'Neill and Leigh 2007; Robins *et al.* 1998), reinforcement of logbook compliance in the short term should become a higher priority.

The motivation behind our study was to address a specific management concern: to what extent the substantial number of records with missing vessel information from the commercial logbooks affects the estimation of trends in fishing power and standardised catch rates. Currently, the strong influence of historical information on vessel characteristics buffers the effect of incomplete information from logbooks. However, this buffering effect may diminish if further years with gaps in logbook vessel information accumulate. For input control fisheries, changes in fleet composition and increases in technical efficiency are likely to continue; therefore, compliance with logbook completion requirements should become a priority. Otherwise, accuracy and precision of fishing power and standardised catch rate estimates may decrease, causing a spill-over effect on stock assessments and the management advice derived from these assessments.

19.6 ACKNOWLEDGEMENTS

This research was supported by the Queensland and Australian Governments through the Australian Fisheries Research and Development Corporation (FRDC 2008/019). This analysis was possible by the contribution to the vessel survey design and collection of vessel information data by C. Turnbull, C. Rose, J. Atfield, B. Mackenzie, C. Barber, and S. Kristle, and by the provision of data by K. Yeomans, and J. Bibby. Finally, we thank Chris Francis and two additional referees for the useful comments and suggestions that contributed to improve our work.

20 Appendix 8. Quantifying northward movement rates of eastern king prawns along eastern Australia

Matias Braccini, Michael F. O'Neill, Anthony J. Courtney, George M. Leigh, Alex B. Campbell and Steven S. Montgomery

M. Braccini · A. J. Courtney (✉) · G. M. Leigh · A. B. Campbell
Agri-Science Queensland, Department of Employment, Economic Development and Innovation, Eco Sciences Precinct, GPO Box 267, Brisbane, QLD 4001, Australia
e-mail: tony.courtney@deedi.qld.gov.au
M. F. O'Neill
Agri-Science Queensland, Department of Employment, Economic Development and Innovation, Maroochy Research Station, 47 Mayers Road, Nambour, QLD 4560, Australia
S. S. Montgomery
Department of Primary Industries, Fisheries Research Centre, 202 Nicholson Pde, Cronulla, NSW 2230, Australia

20.1 ABSTRACT

Movement rates of eastern king prawns, *Melicertus plebejus* (Hess), were estimated from historical and recent conventional tag-recapture information collected across eastern Australia. Data from three studies and 2,656 tag-recaptures were used. Recaptured males and females both moved east-northeast in central Queensland and north-northeast in southern Queensland and New South Wales. Over a period of one year, the estimated transition matrix reflected the species strong northerly movement and the more complex longitudinal movement, showing a very high probability of eastern movement in central Queensland and almost negligible eastern or western movement in northern New South Wales. The high exchange probability between New South Wales and Queensland waters indicated that spatial assessment models with movement rates between state jurisdictions would improve the management of this single unit stock.

20.2 INTRODUCTION

The movement patterns of marine organisms result in complex spatial and temporal organisations such as size, age and/or sex segregation. This, in turn, has fundamental implications for management. For example, movement information is required for determining the spatial scale at which to manage a species. Understanding the movement, spatial and temporal organisation of a species also allows the implementation of powerful management tools (e.g. establishment of nursery area closures; seasonal closures of spawning aggregations) that enhance our ability to conserve stocks and sustain higher yields (Walters and Martell 2004). Therefore, modelling dynamic changes along a species spatial life-history trajectory–the full cycle from egg to spawning–allows identification of spatial policy options for improved management (Walters and Martell 2004).

Most movement models assume a discrete time step and quantify movement rates by estimating a movement transition matrix, i.e. a matrix of probabilities to move from any model cell (e.g. fishing grid squares as specified in fishers' logbooks) to any other cell in each time step (McGarvey and Feenstra 2002). Estimating movement rates and movement transition matrices is therefore essential for the application of spatial population models. In particular, for species with clear movement patterns modelling movements will reduce bias in the calculation of important management quantities such as stock abundance (McGarvey and Feenstra 2002).

Northward movement is an important aspect of the life history of eastern king prawns, *Melicertus plebejus*, in eastern Australian waters. Eastern king prawns have the typical Penaeidae life cycle with an estuarine and oceanic phase (Young 1978; Young and Carpenter 1977). Conventional tagging studies support the single-unit-stock hypothesis with juveniles leaving estuaries and embayments and moving north to spawn (Montgomery 1981; Montgomery 1990; Ruello 1975). The East Australian Current (EAC) may play an important role in the species' distribution, transporting the planktonic larvae south to the estuaries and embayments where they grow (Montgomery 1981). In addition, eastern king prawns are capable of moving very large distances, with one individual moving 1,333 km in just 184 days (Montgomery 1981). The combined effects of larval transportation by the EAC and the high movement capabilities of maturing and adult eastern king prawns result in a large geographical distribution for the species, ranging from 21º S to 41º S (Figure 20-1).

Eastern king prawns have been commercially targeted for > 60 years mostly from Fraser Island (25º S) south to the Gippsland Lakes (38º S) with the fishery expanding northwards to Swain Reefs (21º S) in the last three decades (Montgomery 1990). Movement patterns of eastern king prawns have mostly been determined from individuals released south of 28º S (Montgomery 1990) . However, the bulk of the catch (>80%) is taken north of Coffs Harbour (30º S). Despite eastern king prawns constituting a single-unit stock, this resource is currently managed as separate stock units based on state government jurisdictions (Montgomery 1990). Ignoring the flow of individuals between jurisdictions can cause inaccurate estimates of fishing mortality and management advice (McGarvey and Feenstra 2002). Currently, quantification of movement rates has been restricted to New South Wales (Gordon *et al.* 1995; O'Callaghan and Gordon 2008). Construction of movement transition probabilities (matrix) for the entire range of the species is required for spatial stock models and improved management.

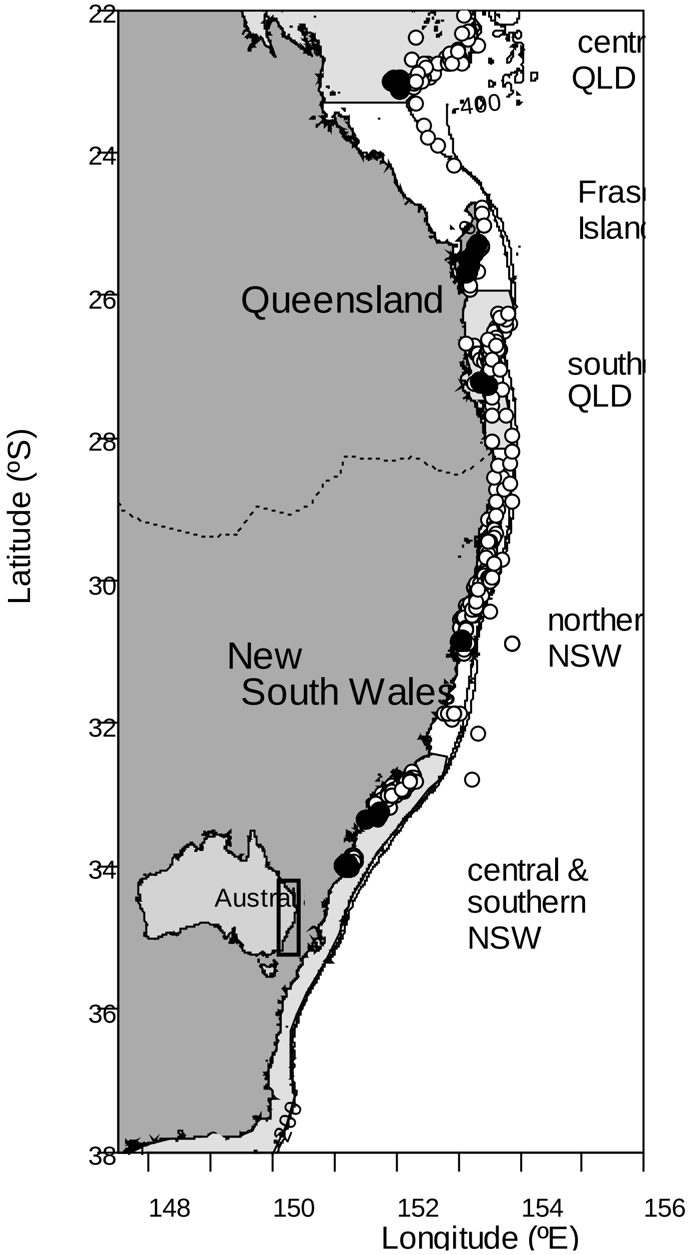


Figure 20-1. Map of the main eastern king prawn stock area, eastern Australia. Shown are the depth contours (200 and 400 m isobaths), and the distribution of recaptures (open circle) for prawns released (solid circle) in central Queensland (QLD), Fraser Island, southern Queensland, and northern, and central and southern New South Wales (NSW).

To describe the overall movement characteristics of the species within its geographical distribution, all available data from tag-recapture experiments undertaken in New South Wales and southern Queensland were combined with data from an unpublished 2009–2011 tag-recapture study in the species northern-most distribution (central Queensland). In addition, an explicit quantification of the movement rates of eastern king prawns is provided through the construction of a movement transition matrix.

20.3 MATERIALS AND METHODS

20.3.1 Tagging experiments

Movement rates of eastern king prawns were estimated using data from several tag-recapture experiments that investigated the movements, migration, population dynamics and fishery for eastern king prawns (Table 20-1). Raw data from studies by Lucas (1974), Ruello (1975), Potter (1975), Glaister *et al*. (1987; 1990) and Montgomery (1990) were not available and indeed are not known to still exist.

For the quantification of movement patterns and rates, recaptured prawns were allocated to one of five large regions based on the coast physiographic characteristics and the release latitude: central Queensland, Fraser Island, southern Queensland, northern New South Wales, and central New South Wales. Recaptures occurring within two days of release were excluded on the assumption that these individuals have not fully recovered from the tag-and-release process, hence not reflecting normal prawn behaviour (Lucas 1974). In addition, 756 recaptures from Gordon *et al*. (1995) were excluded due to inconsistencies in the reporting of the recapture information.

20.3.2 Movement pattern

Movement patterns were quantified by taking the position of release and recapture locations as start and end points of the movement paths. This information was used to calculate the distance (km) and trajectory (measured in whole-circle bearing degrees, with 0º representing true east). A Chi-square test was used to evaluate differences in the sex ratio of recaptured males and females and a Kolmogorov-Smirnov test was used to compare the size distribution of released and recaptured prawns. Following Jones (1976), the direction of movement of the population was calculated as a summary of the overall movement pattern. Bootstrap methods (1000 replicates) were used to estimate confidence intervals (2.5 and 97.5 percentiles) around mean direction of movement estimates.

20.3.3 Movement rate

The estimation of movement rates involved three main steps. First, the number of spatial fishing grid squares (30 × 30 minute) was determined. The movement study covered a very large area (Figure 20-1). To reduce the number of unnecessary calculations, the analysis only included grid squares where eastern king prawns have been historically caught. For individuals released in Queensland, the historical distribution of Queensland eastern king prawn catches from logbook data was used to select the squares. For New South Wales, historical eastern king prawn logbook catches had not been reported at a 30 × 30 minute resolution but at one degree latitudinal bands, except from 2009 onwards, when catches started to be reported with a corresponding latitude and longitude. Therefore, the New South Wales historical catch from each one-degree band was allocated into 30 × 30 minute grids using the recent high-resolution spatial information on catch and effort distribution and bathymetry information (under the assumption that eastern king prawns are not caught deeper than 300 m).

Table 20-1. Summary of eastern king prawns *Melicertus plebejus* tag-release studies.

Study	**Study period**	**Tag and release area**	**Tag type**	**Number tagged and released**	**Number recaptured**	**Study objective**	**Were the data used in current study?**
Lucas (1974)	1969–71	Moreton Bay and adjacent offshore areas (27º–28ºS)	Modified Petersen disk attached to abdomen with bent pin	25,655	3,104	Quantify fishing mortality, natural mortality, emigration (from Moreton Bay) and growth rates.	No, data unavailable
Ruello (1975)	1969–72	New South Wales coast from Clarence River to Merimbula Lake (30º–37ºS)	Atkins-type tags	18,197	297	Measure estuarine emigration rates and oceanic migration.	No, data unavailable
Potter (1975)	1971–72	Moreton Bay, Wide Bay Bar and deepwater prawn trawl grounds adjacent to Mooloolaba (26º–28ºS)	Plastic disc attached to abdomen with bent stainless steel pin	29,659	3,656	Describe movements in Moreton Bay, Jumpinpin, Wide Bay and deepwater grounds off Mooloolaba.	No, data unavailable
Glaister et al. (1987) and (1990)	1979–80	Ballina, Clarence River, Evans Head and Brunswick Heads (29º–30ºS)	Polyethylene streamer tags	19,898	3,488	Measure growth, migration, tagging mortality and fishing mortality rates.	No, data unavailable

Montgomery (1990)	1979–82	Gippsland Lakes, Victoria, to offshore from Clarence River, New South Wales (29º–38ºS)	Individually numbered Floy streamer tags inserted through abdomen	26,504	755	Describe stock structure and movements, including prawns from the southern limits of their distribution (> 34ºS).	No, data unavailable
Die et al. (1994)	1990–91	Moreton Bay, offshore Moreton Island and Wide Bay Bar (25º–27ºS)	Individually numbered Floy streamer tags inserted through abdomen	9,750	1,317	Describe movement and growth to assess spatial closures on yield and value.	Yes
Gordon et al. (1995)	1979–82 and 1991–92	New South Wales coast (31º–34ºS)	Individually numbered Floy streamer tags inserted through abdomen	11,408	2,312	Model migration in the oceanic fishery of New South Wales	Yes
Present study	2009–10	Fraser Island and North Reef (23º–25ºS)	Individually numbered Floy streamer tags inserted through abdomen	3,766	83	Quantified movement and growth in the northern most distribution for the species	Yes

The next step in the estimation of movement rates involved the weighting of the number of recaptures per grid square. Recaptured eastern king prawns were reported by the Queensland and New South Wales commercial trawl fishers. To reduce the biasing effect of the heterogeneous distribution of fishing effort on tag recaptures, recaptures were weighted by the time at liberty (to give more weight to records with longer time at liberty as these are more likely to represent true movement) and adjusted for the effective fishing effort in the month and year of recapture (Wright *et al.* 2006). Standardised effective fishing effort was calculated as:

$$E'_{jk} = fp_{jk} E_{jk}$$

where E'_{jk}, fp_{jk} and E_{jk} are the standardised effective fishing effort, the relative vessel fishing power (Braccini *et al.* 2012a) and the nominal fishing effort (sourced from the Queensland commercial otter trawl compulsory daily logbook records between 1988 and 2010) and from the New South Wales Ocean Trawl Fishery records between 1984 and 2010 during month *j* and year *k*. The Queensland fishing power (fixed terms only) was allocated to New South Wales records because no information on vessel and gear characteristics was available (Braccini *et al.* 2012a). The standardised number of observed recaptures was calculated as:

$$R'_{ijk} = \frac{R_{ijk}}{E'_{jk}}$$

where R'_{ijk} and R_{ijk} are the standardised number of recaptures and the number of observed recaptures in cell *i*, during month *j* and year *k*.

The final step in the estimation of movement rates involved the construction of a movement transition matrix (Hilborn 1990) where the proportion of individuals moving from a source grid square *i* to a destination square *j* is given by the matrix element P_{ij}. To avoid the problem of tag non-reporting, recapture probabilities were expressed as proportions of the number of released individuals recovered (McGarvey and Feenstra 2002). Following Walters and Martell (2004), an "Eulerian" representation was used to model the movement among spatial fishing grid squares (i.e. the probabilities of individuals moving) in each time step. A time step of seven days was used to make it unlikely that eastern king prawns would move more than one spatial grid per step. A velocity vector in longitude (east–west movement direction) and latitude (north–south movement direction) components was obtained assuming straight-line movement between release and recapture locations. Given that release location can affect the proportion of individuals moving among grid squares (e.g. an individual released close to the edge of a grid square is more likely to move to an adjacent grid square than an individual released in the middle of the grid square), release-recapture data were replicated to reduce bias due to the position of release locations within a grid square (Turnbull *et al.* 2009). Hence, for each grid square from which tags were released (release grids), 100 coordinate locations were randomly generated through bootstrapping. Next, the velocity vectors were relocated to each of the randomly generated locations and the respective destination coordinates were obtained. Next, the number of destination points inside each square was counted and the probability of individuals moving from release squares to surrounding recapture grids was estimated. For this estimation, a generalised linear model (GLM) with a binomial distribution and a logit link function was used. The model was defined as:

$$\log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \beta_0 + \beta_1 + \beta_2 x_2 + \varepsilon$$

where p_{ij} is the probability of the jth prawn released in a grid square moving into the ith site (nine possible destination sites relative to the release site were defined: north-west (NW), west (W), south-west (SW), north (N), stay in site (stay), south (S), north-east (NE), east (E), southeast (SE)), β_0 is the intercept, β_1 is a vector of coefficients for the destination site, β_2 is the coefficient for the interaction between the destination site and region, and ε is the error term. All grid squares within the fishing grounds were allocated to a region and this information was used in the GLM model to predict the movement probabilities for all grid squares. Statistical analyses were carried out using the statistical package R (R Development Core Team 2012).

20.4 RESULTS

20.4.1 Movement pattern

Between 1969 and 2011, eight discrete tag-recapture studies were undertaken on eastern king prawns (Table 20-1). Approximately 144,837 eastern king prawns were tagged and released in these studies, from which 14,988 recaptures have been reported. Tag-recapture information was only available for three of the eight studies. For the available information, between 1979 and 2011, 3,712 tagged and released eastern king prawns were reported. Of the 3,712 recaptures, 2,656 were included in the analyses. Most of the recaptured eastern king prawns were released at Fraser Island and central New South Wales, followed by northern New South Wales, southern Queensland and central Queensland (Table 20-2).

Table 20-2. Sample size used in the analyses and population movement direction (in degrees, with 0º representing true east) for all regions combined and by region calculated from recaptured eastern king prawns.

		Movement direction (º)		
Region	**N**	**Lower 95% CI**	**Median**	**Upper 95% CI**
Overall	2,656	60.05	62.64	65.01
Central QLD				
males	25	16.68	23.29	28.30
females	38	16.36	23.05	29.00
Fraser I.				
males	415	19.76	53.71	87.01
females	533	18.17	54.73	86.84
unknown	6			
Southern QLD				
males	110	67.48	79.79	87.20
females	121	69.23	82.32	89.60
Northern NSW				
males	80	65.12	71.33	78.79
females	91	65.93	72.72	76.23
unknown	402			
Central NSW				
males	214	52.26	63.14	67.73
females	303	55.40	61.30	66.26
unknown	318			

The sex ratio of recaptured prawns was skewed towards females for Fraser Island (Chi-square test, X^2_2 = 14.688, P < 0.001) and central New South Wales (X^2_2 = 15.321, P < 0.001) but showed no differences for central (X^2_2 = 2.683, P = 0.101) and southern Queensland (X^2_2 = 0.5238, P = 0.469) and northern New South Wales (X^2_2 = 0.708, P = 0.402). The distribution of recaptured individuals covered the full size range of eastern king prawns recruited to the fishery (Figure 20-2). Recaptured individuals were significantly larger than when released (Kolmogorov–Smirnov, $Z = 0.366$, $P < 0.001$). Ninety five percent of recaptured eastern king prawns were at liberty for up to 153 days (median= 30.0 days), and travelled up to 129 km (median=3.6 km) at an estimated speed of up to 2.0 km/day (median= 0.16 km/day) (Figure 20-3). Some individuals, however, were at liberty for > 600 days and travelled > 800 km at speeds > 4.70 km/day.

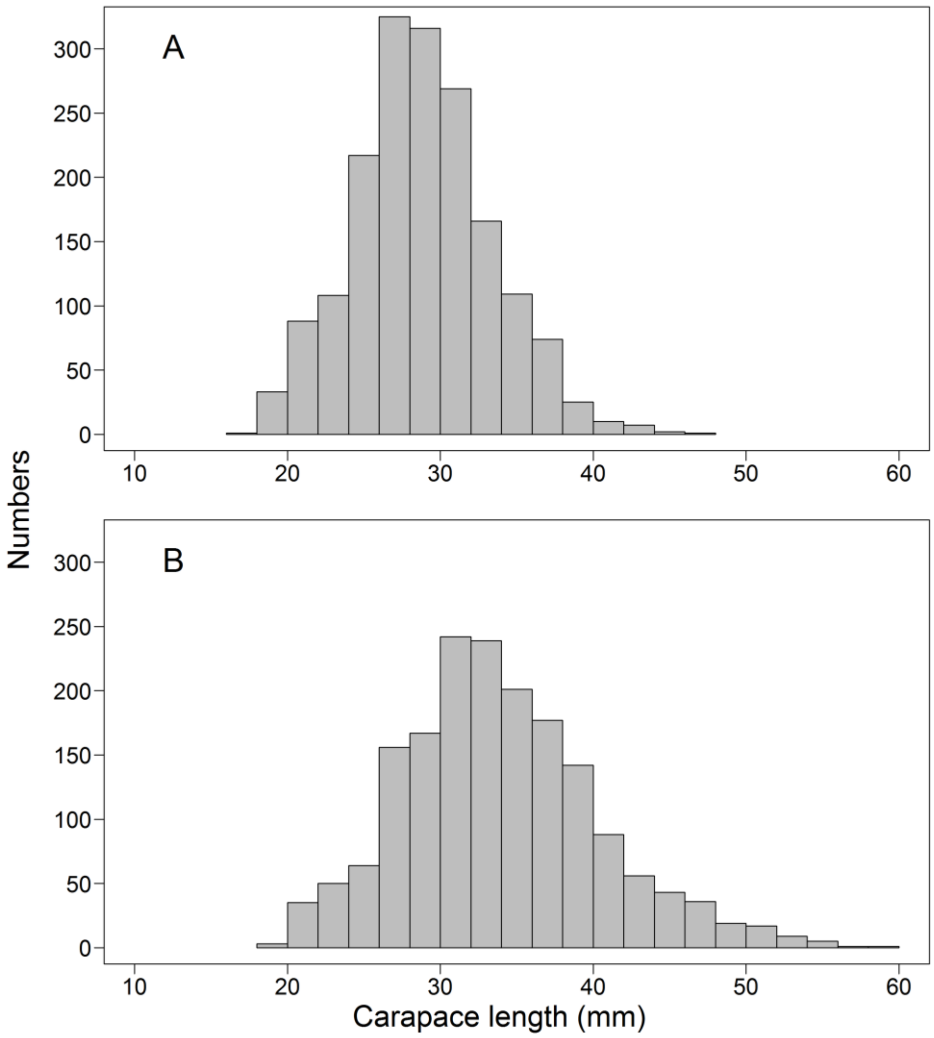


Figure 20-2. Carapace length distribution of recaptured eastern king prawns at release; b at recapture.

For the different release regions, recaptured males and females moved in a similar direction (Table 20-2). Individuals released in southern Queensland, northern New South Wales and central New South Wales mostly moved in a north-north-easterly direction, whereas individuals released at Fraser Island moved in a north-easterly direction, and those released in central Queensland moved in an east-north-easterly direction. From Fraser Island and to a lesser extent, Southern Queensland, released individuals showed a broader and more diverse movement direction (i.e. wider confidence intervals), than in other regions where movement was more directed (i.e. tighter confidence intervals).

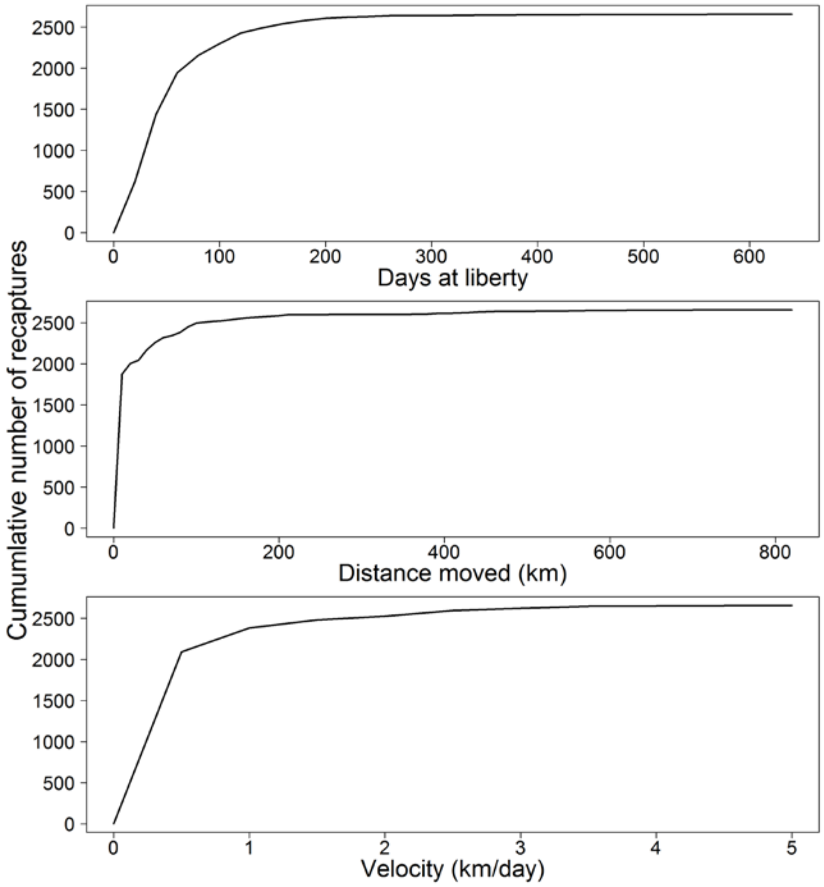


Figure 20-3. Cumulative distribution of days at liberty, distanced moved and velocity for recaptured eastern king prawns.

20.4.2 Movement rate

There was a significant site effect and interaction effect between site and region, reflecting the directional movement pattern and geographical differences in the movement of eastern king prawns (Table 20-3). Due to the very large number of 30 × 30 minute grid squares (106) represented in the transition matrix, interpretation of movement rates is not straightforward from simply plotting the fishing grid squares. To aid visualisation of movement rates within a year period, longitudes were combined to show movement rates across latitude (Figure 20-4) and latitudes were combined to show movement across longitude (Figure 20-5).

Table 20-3. Test of significance of main site effect and interaction effect of site and release region

Source	d.f.	Deviance	X^2 probability
Site	8	20216822.2	<0.001
Site.Region	36	444344	<0.001

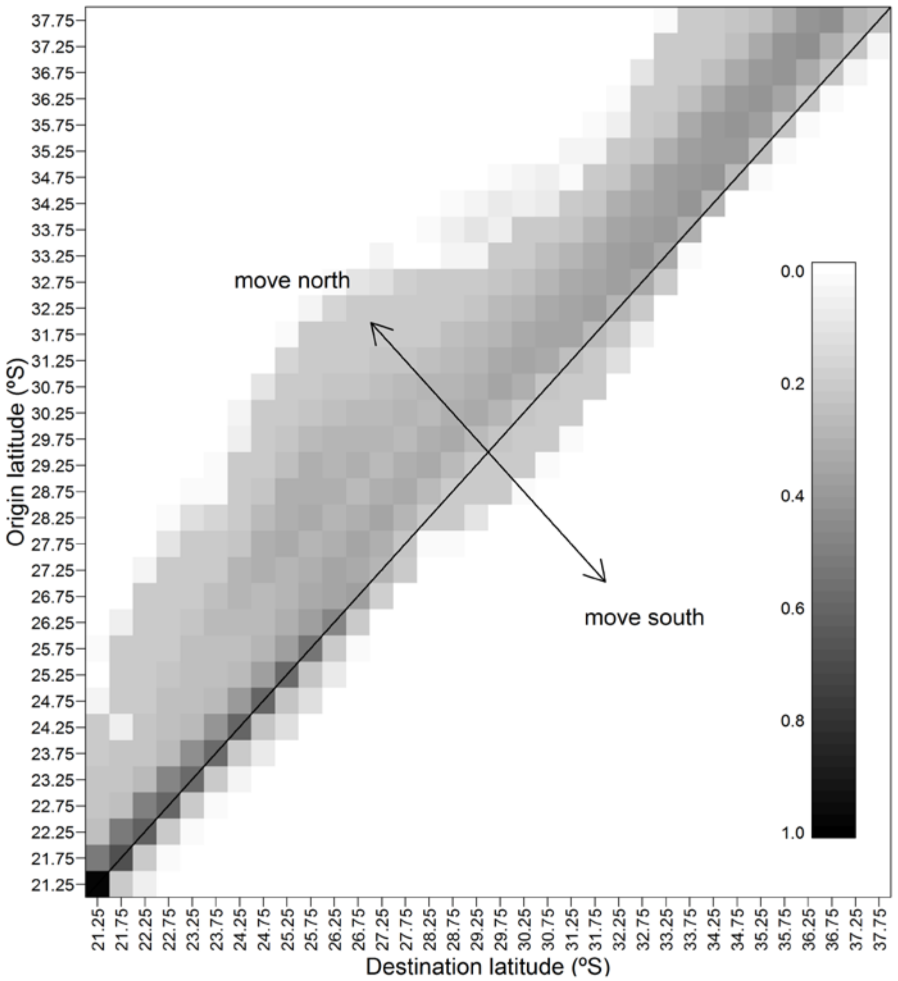


Figure 20-4. Estimated movement transition matrix showing movement across latitude. Values indicate the proportion of individuals moving from one latitudinal band (origin) to another (destination) in one year period. The main diagonal indicates proportion of individuals staying in the same band; values above the diagonal indicate movement to the north and values below, movement to the south.

Over a year period, there was considerable northward movement away from the release latitudinal band indicated by the relatively lower probability values on the main matrix diagonal for most latitudes (Figure 20-4). For the northern latitudinal bands (21.25–23.25º S), there was a higher probability of recapturing a released individual in the band where it was released given that these latitudinal bands constitute the northern end of the species distribution and show the combined probability of staying in the band and of moving further north. Intermediate latitudes (29.25–32.25º S) showed the longest northerly movement, indicated by the wide range of destination latitude probabilities above the main matrix diagonal. For all latitudinal bands, there was very low probability of southerly movement (i.e. probabilities below the main matrix diagonal).

Due to the different longitudinal movement patterns shown at different latitudes, longitudinal transition matrices are shown separately for central Queensland, southern Queensland, northern New South Wales, and central and southern New South Wales (Figure 20-5). Individuals released in central Queensland showed a high probability of eastern movement (i.e. probabilities below the main matrix diagonal), particularly for individuals released in the western-most longitudes (149.75–152.25º E) (Figure 20-5a). Individuals released in southern Queensland showed low probability of movement across longitudes (i.e. high probability values on the matrix diagonal) although there was some probability of easterly (mostly between 151.75 and 152.25º E) and westerly (mostly between 152.75 and 154.25º E) movement (Figure 20-5b). Individuals released in northern New South Wales showed low probability of movement across longitudes between 153.25 and 153.75º E and high probability of easterly movement in 152.75º E (Figure 20-5c). Individuals released in central and southern New South Wales showed relatively low probability of being recaptured in the release longitudinal band and a higher probability of recapture in the adjacent longitudinal band to the east (Figure 20-5d).

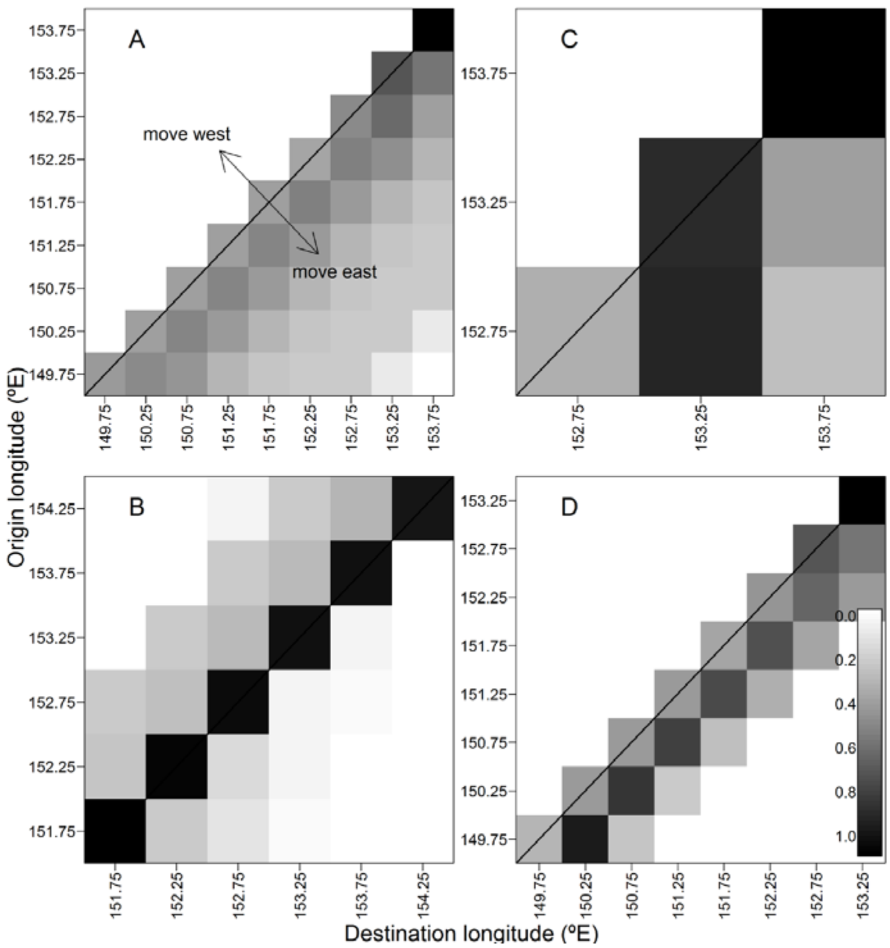


Figure 20-5. Estimated movement transition matrices showing movement across longitude for different regions: a central Queensland; b southern Queensland; c northern New South Wales; d southern and central New South Wales. Values indicate the proportion of individuals

20.5 Discussion

The study made use of all available release-recapture information for eastern king prawns collected by previous studies in several regions along eastern Australia over the past 30 years. In addition, previously unpublished (Die *et al.* 1999) and more recent tagging information for the species northern-most distribution was summarised and included in the quantification of movement. Estimates obtained in this study, therefore, represent the movement patterns and rates of eastern king prawns along their main geographical distribution.

The quantitative re-analysis of archived published information combined with the analysis of unpublished and recent tagging information provided strong support to the concept of the highly directed northerly migratory movement of eastern king prawns between southern New South Wales and Fraser Island. This pattern was consistent with previous tagging experiments (Glaister *et al.* 1987; Lucas 1974; Montgomery 1990; Potter 1975; Ruello 1975). There were, however, differences in the movement direction of individuals released in other regions. North of southern Queensland, eastern king prawns maintained an overall northerly movement but showed an increased tendency to disperse, coinciding with the widening of the continental shelf (Figure 20-1). South of southern Queensland, the continental shelf is very narrow, restricting the movement of eastern king prawns to a narrow path (Glaister *et al.* 1987; Montgomery 1990; Ruello 1975). Once the continental shelf widens, eastern king prawns broaden their movement patterns and disperse as shown by the wider confidence intervals of direction for individuals released in Fraser Island compared to the tighter intervals for individuals released in New South Wales. Individuals released in central Queensland (23º S) showed different movement direction from individuals released further south, moving mostly to the east across a much wider continental shelf. Overall, the information indicates that eastern king prawns are generally restricted to the continental shelf, moving along a narrow path when the continental shelf narrows and dispersing further across a wider area when the continental shelf widens.

Previous tagging studies on *M. plebejus* have led authors to hypothesise on the species' stock structure. Ruello (1975), based on the northward migration and mixing of individuals from different New South Wales estuaries, proposed a single adult stock. This was supported by an enzyme polymorphism study that showed genetic homogeneity in samples from southeast Queensland (27º S) to Victoria (38º S) (Mulley and Latter 1981). Montgomery (1990) confirmed the northward migration and mixing of prawns, supporting Ruello's single stock hypothesis. Glaister et al. (1987) acknowledged the mixing of adults but argued that, for stock assessment purposes, there were two substocks based on the origin of recruits. These were referred to as the Moreton Bay–Mooloolaba substock, with recruits principally from Moreton Bay, and the New South Wales Southport–Mooloolaba substock with recruits principally from the New South Wales estuaries. The existence of a Moreton Bay–Mooloolaba substock was supported by the earlier work of Lucas (1974) and Potter (1975). The latter, based on the recaptures of tagged prawns released in southeast Queensland, suggested that a physical "boundary between stocks", comprised of a system of sand bars, existed north of Moreton Island. Uncertainty about the stock structure increased in the 1980s when additional fishing grounds for *M. plebejus* were established further north and further offshore, near the Swain Reefs (22º S) (Dredge and Gardiner 1984). Preliminary genetic assessments of the stock structure based on mitochondrial DNA and microsatellite markers support the single-stock hypothesis with no significant evidence to suggest isolated populations throughout the species overall range (J.T. Chan pers. comm.).

The estimated movement transition matrix was able to represent the process of extensive movement of eastern king prawns. The model-based approach adopted for predicting movement probabilities reflected the overall northerly migratory movement of the species across latitudes and the more complex movement rates and patterns across longitudes. The matrix showed how the movement behaviour of eastern king prawns differs across their geographical distribution; a behaviour resulting from eastern king prawns being restricted to moving along a very narrow continental shelf in New South Wales but then making use of a much broader shelf in southern and central Queensland, hence expanding their movement patterns.

The approach used for the construction of the movement transition matrix provides a framework for estimating movement rates across a very large region (17 degrees in latitude by six degrees in longitude). This approach has both advantages and weaknesses. By conditioning estimation of movement parameters to the relative proportions recaptured, the influence of tag non-reporting, tag loss, survival rates and tag-induced mortality is reduced (McGarvey and Feenstra 2002). Given that the restricted northerly movement pattern in New South Wales may be an artefact of the heterogeneous distribution of fishing effort (Montgomery 1990), recapture information was standardised by time at liberty and effective fishing effort to reduce such a biasing effect. The estimation of movement parameters was based on nine tag release events in inshore waters, covering only nine of the possible 106 fishing grid squares modelled. In addition, no information from offshore release locations or southern New South Wales locations was available. The estimated parameters were used to predict the movement of individuals released in all the fishing grids modelled (on the assumption that within a region, individuals exhibit the same movement behaviour). However, if there were considerable within-region differences in movement behaviour and these were not captured in the model, movement predictions could be biased.

The study results showed that re-analysing historical tagging data in combination with recent tagging data from the northern-most distribution of eastern king prawns provided a considerable insight into the movement behaviour of the species. This, in turn, is an important piece if information for management improvement. Eastern king prawns are one of the most mobile crustaceans but they are managed as two separate stocks based on state jurisdictions. The transition matrix, however, showed a high exchange rate between New South Wales and Queensland within the period of a year. Therefore, the assumption that the rate of movement among state jurisdictions is negligible is not valid. Rather, a spatially explicit modelling approach that considers the exchange rate of individuals between states is required for improved stock assessment. This would allow assessing the impact of different effort distributions on the proportion of prawns surviving and moving to the spawning grounds to ensure that enough spawners survive the migration and maintain a sustainable stock level.

Acknowledgements This research was supported by the Queensland and Australian Governments through the Australian Fisheries Research and Development Corporation (FRDC 2008/019). We thank the commercial trawl fishers in Queensland and New South Wales who provided the information on recaptured tagged prawns.

21 Appendix 9. Stochastic growth of the eastern king prawn (*Melicertus plebejus*) harvested off eastern Australia

J. Matías Braccini[1,5], Vladimir S. Troynikov[2], Anthony J. Courtney[1], David J. Die[3], Andrew Prosser[1] and Steven S. Montgomery[4]

[1]Agri-Science Queensland, Queensland Department of Employment, Economic Development and Innovation, Ecoscience Precinct, Brisbane, QLD 4102, Australia
[2]Department of Zoology, University of Melbourne, Parkville, Vic. 3052, Australia
[3]University of Miami, 4600 Rickenbacker C., Miami, FL 33148, USA
[4]New South Wales Department of Primary Industries, Cronulla Fisheries Research Centre, Cronulla, NSW 2230, Australia

[5]e-mail: matias.braccini@deedi.qld.gov.au
Running head: Growth of eastern king prawns

21.1 ABSTRACT

Stochastic growth models were fitted to length-increment data of eastern king prawns, Melicertus plebejus, tagged across eastern Australia. The estimated growth parameters and growth transition matrix are for each sex representative of the species' geographical distribution. Our study explicitly displays the stochastic nature of prawn growth. Capturing length-increment growth heterogeneity for short-lived exploited species such as prawns that cannot be readily aged is essential for length-based modelling and improved management.

Key words — Eastern king prawn, stochastic growth model, tag-recapture information

21.2 INTRODUCTION

Growth estimates of prawns are commonly derived from length-increment data under captive (Do Thi Thanh *et al.* 2010) and field (Wang *et al.* 1995) experimental conditions. Eastern king prawns, Melicertus plebejus (Hess, 1865), an eastern Australia endemic species, has the typical life cycle of commercial penaeids with an estuarine and oceanic phase (Young and Carpenter 1977). Melicertus plebejus undertake an extensive migration from southern New South Wales to central Queensland, constituting the basis of commercial trawl fisheries in both states. Lucas (1974) produced growth estimates based on tag-recapture data from 51 females and 44 males released in Moreton Bay, Queensland. Ruello (1975) presented length-increment data for 38 individuals released across New South Wales but did not fit a growth model to these data. Glaister *et al.* (1987) produced growth estimates based on tag-recapture data from 87 females and 70 males released in northern New South Wales. These studies used deterministic growth models, providing only average values of growth parameters and ignoring the natural variation in growth among individuals generated by spatial and temporal variations in food, temperature and other environmental factors. Furthermore, growth estimates derived from these studies are based on small sample sizes restricted to a fraction of the species distribution. Given that M. plebejus are considered to form a single-unit stock across whole eastern Australia (Montgomery 1990), growth estimates representative of the whole stock are required. In addition, quantitative management advice for hard-to-age species such as prawns, crabs and rock lobsters is derived from size-structured population dynamics models (Punt *et al.* 2009). For implementing such models, a size-transition matrix (i.e. the probability of growing from one size-class to each of a range of other size classes in a set time step) is required.

21.3 MATERIAL AND METHODS

Stochastic growth models were fitted to all available tag-recapture information on M. plebejus released across eastern Australia over the past 35 years (Figure 21-1). Growth length-increment data (i.e. length at release, days at liberty and length at recapture) from all tag-recapture studies on M. plebejus across eastern Australia were re-analysed, with the exception of data from Lucas (1974), Potter (1975) and Montgomery (1990), which were unavailable. In addition, data from Gordon *et al.*(1995) were included in the analysis (Table 21-1). In each study, Floy streamer tags were inserted through the abdomen of the prawn, between the dorsal gut and the ventral nerve chord. As an incentive to fishers, small financial rewards were provided for each recaptured prawn. All recaptures were caught by commercial otter trawl fishers in Queensland or New South Wales who provided information on the location and date of recapture. Small negative growth increments (n= 13 males and nine females) were considered as measurement errors and were set equal to 0. Prawns at large for less than 28 days after release were removed from the analyses based on the assumption that these individuals had not moulted or grown (Ruello 1975). Changes in growth rates over time or space were not tested. Although such effects have been reported for exploited crustaceans, the tag-recapture data available for M. plebejus have little or no spatial and temporal overlap. Hence, it would be difficult to explain/quantify the factors contributing to differences in parameter estimate values, such as separating the effects of time (e.g. seasonal changes and environmental shifts) and space (e.g. habitat variation).

Three versions of a two-parameter von Bertalanffy–Fabens growth model (VB–FGM) in the form of conditional probability density functions (pdf) were developed on the assumption that the growth parameter k varies among individuals according to Weibull, gamma and log-normal pdf (Troynikov 1998). In these models, for any initial size l_1 and any finite time at liberty Δt, individual size varies within the interval (l_1, L_∞), where L_∞ is an estimated "upper limit" of size in a population. Kullback–Leibler divergence was used to compare the performance of the alternative stochastic models in fitting the data (Troynikov and Walker 1999). For a detailed description of the modelling framework and parameterisation see Troynikov (1998), Troynikov and Walker (1999) and Punt *et al.* (2006). Growth parameters were estimated for males and females and compared based on likelihood ratio tests (Kimura 1980). The size-transition matrix $\{X_{i,j} : i, j = 1..m\}$ was calculated by numerically integrating $p(l_j|l_i, \Delta t)$ the conditional pdf of growing from size l_i to size l_j, where m is the number of size-classes. This defines the probability of an animal in size-class Δi growing into size-class Δj over a time-step Δt, where $\sum_j X_{i,j} = 1$. Note that the growth transition matrix can be obtained for any resolution in time and size-step that will suit requirements of any population dynamic model.

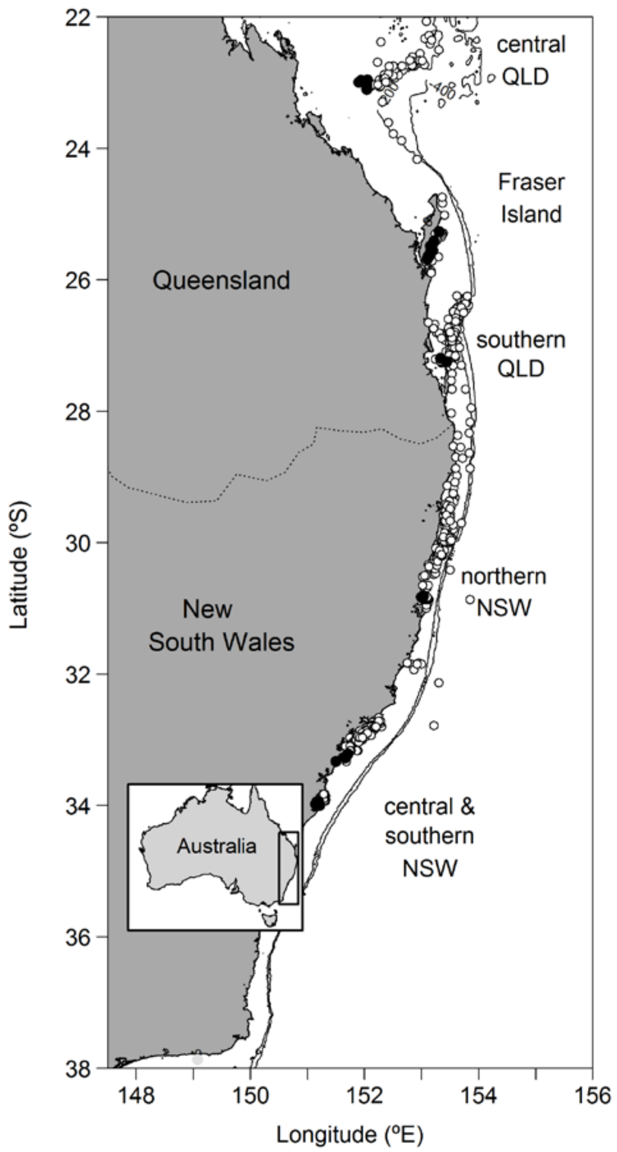


Figure 21-1. Spatial distribution of <u>Melicertus plebejus</u>. Also shown is the location of tag-released (solid circle) and recaptured (open circle) individuals.

Table 21-1. Summary of the tag-recapture information used in growth analyses.

Area	**Tagging period**	**Recapture numbers**	**Tagging study**
Central Queensland	Jan 2009 and Feb 2010	61	Braccini *et al*., unpublished
Fraser Is	Nov 1990 and Jan 2009	278	Die et al., (1999); Braccini *et al*., unpublished
Southern Queensland	Nov 1990 and Feb 1991	161	Die et al., (1999)
Northern New South Wales	Nov 1991 and Jan 1992	162	Gordon *et al*.(1995)
Whole New South Wales	Jan, Feb, Mar 1969, 1971 and 1972	27	Ruello (1975)
Northern New South Wales	Jan, Mar, May 1979 and 1980	133	Glaister *et al.* (1987))
Central New South Wales	Feb, Oct, Nov, Dec 1991 and Jan, Feb, Mar 1992	118	Gordon *et al*.(1995)

21.4 RESULTS

Parameter estimation was done on tag-recapture data from females 16–55 and males 18–42 mm carapace length (C_L) at release (Figure 21-2a and d). These individuals were at large between 29 and 376 (females) and 29 and 623 (males) days (Figure 21-2c and f). There were significant differences in the growth of males and females ($P < 0.001$) with males growing faster and attaining smaller L_∞ (Table 21-2), a common pattern observed in other prawn species.

The stochastic VB–FGMs provided similar growth parameters (Table 21-2). The model with Weibull pdf for k provided the best fit to the growth increments of females and males. The model with log-normal pdf failed to converge. For comparing growth parameters between different stochastic models, the values of mathematical expectation E[k] and standard deviation SD[k] were recalculated from the maximum likelihood estimates of the parameters of Weibull and Gamma pdf, i.e. E[k] and SD[k] are not estimated directly. The relations between these parameters and values E[k] and SD[k] are not linear; therefore, standard errors for E[k] and SD[k] are not available. Parameters in deterministic and stochastic models have different biological meaning: in the case of stochastic models, L_∞ represents the population upper limit for maximum size whereas in deterministic models L_∞ is the predicted maximum average length (Troynikov and Walker 1999); hence, they are not comparable. The smaller sizes of females and males showed higher heterogeneity in growth than did larger animals (Figure 21-3). For a time interval of 1 year and initial sizes of 20, 30 and 40 mm C_L, females showed larger length increments and more variability in growth (i.e. wider distribution) than males. The higher variability in the size increment of females reflects the higher heterogeneity in their individual growth, possibly due to their higher energetic investments in reproduction. Note that 20 mm is the size at recruitment in population dynamic models then, given constant recruitment, plots for pdf $p(\Delta l \mid l = 20\text{mm}, \Delta t\text{=1month})$ can be viewed as a normalised size distribution of 1 month old unfished population (Figure 21-3).

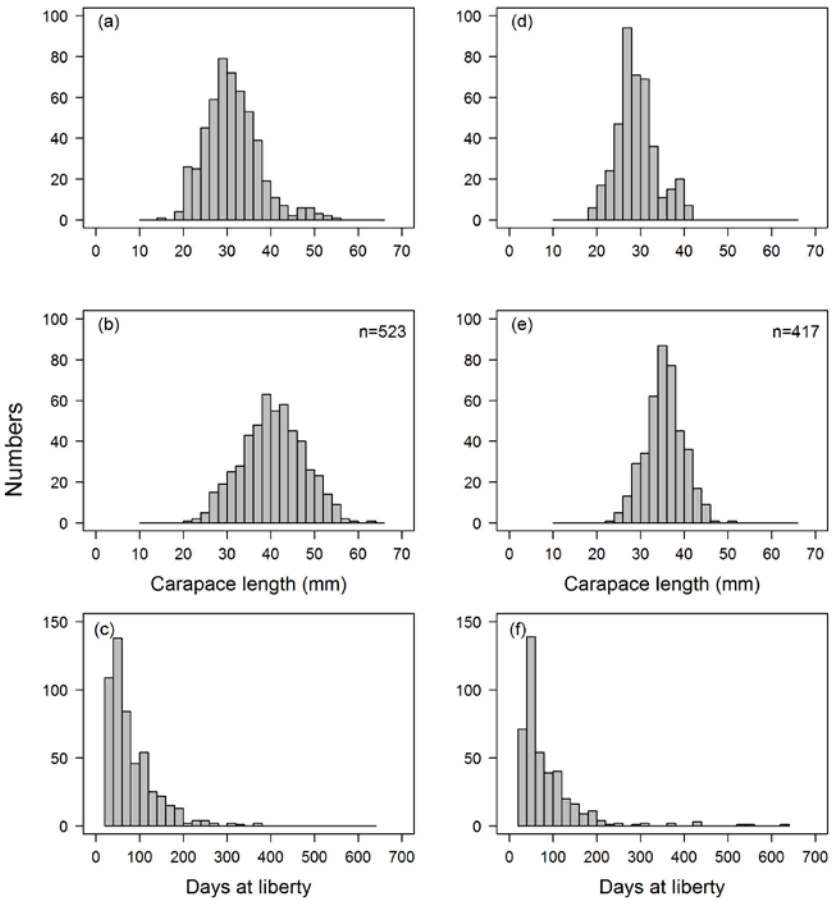


Figure 21-2. Size frequency distribution of (a) released and (b) recaptured female and (d) released and (e) recaptured male Melicertus plebejus. Also shown is the distribution of days at liberty of (c) females and (f) males.

Table 21-2. Parameter estimates of the stochastic models for female (n=523) and male (n=415) Melicertus plebejus. SE (%), percentage standard error; L∞, upper limit (in the stochastic case) and average maximum (in the deterministic case) carapace length (mm); E[k], mathematical expectation of k ($year^{-1}$); SD[k], percentage of standard deviation (representing heterogeneity in the population rather than statistical error) for the stochastic models. Parameters from the deterministic and stochastic models have different biological meaning so they are not strictly comparable.

Model	**Parameter**	**Females**		**Males**	
		Estimate	**SE(%)**	**Estimate**	**SE(%)**
k–Weibull	L∞ (mm)	64	43	48	30
	E [*k*] ($year^{-1}$)	1.688		2.186	
	SD [*k*]	46		53	
k–Gamma	L∞ (mm)	64	83	47	59
	E [*k*] ($year^{-1}$)	1.722		2.393	
	SD [*k*]	49		50	
Deterministic	L∞ (mm)	57	24	43	15
VB–FGM	*k* ($year^{-1}$)	2.307	78	3.274	80

Table 21-3 lists the size-transition matrix of females and males for a time-step of one month and a size-step of 5 mm in C_L, commonly applied steps in stock assessment models for prawns. Note that the differences in E[*k*], SD[*k*] and L_∞ values between models with k-Weibull and k-gamma distributions is quite small (Table 21-2); therefore, the differences between matrices calculated from those two parameter sets were negligible so only the model that showed the most support is shown.

Table 21-3. Size-transition matrix for (a) females and (b) males for a time-step of one month and size-step of 5 mm C_L (based on the k-Weibull model)

Proportion of animals in each 5-mm length-class growing to each 5-mm length-increment class in a monthly time step									
(a)	20	25	30	35	40	45	50	55	60
20	0.144	0	0	0	0	0	0	0	0
25	0.646	0.185	0	0	0	0	0	0	0
30	0.207	0.691	0.243	0	0	0	0	0	0
35	0.003	0.124	0.701	0.325	0	0	0	0	0
40	0	0	0.056	0.661	0.436	0	0	0	0
45	0	0	0	0.014	0.563	0.575	0	0	0
50	0	0	0	0	0.001	0.425	0.727	0	0
55	0	0	0	0	0	0	0.273	0.880	0
60	0	0	0	0	0	0	0	0.120	1
Total	1	1	1	1	1	1	1	1	1

Proportion of animals in each 5-mm length-class growing to each 5-mm length-increment class in a monthly time step						
(b)	20	25	30	35	40	45
20	0.257	0	0	0	0	0
25	0.672	0.355	0	0	0	0
30	0.071	0.631	0.501	0	0	0
35	0	0.014	0.499	0.691	0	0
40	0	0	0	0.309	0.895	0
45	0	0	0	0	0.105	1
Total	1	1	1	1	1	1

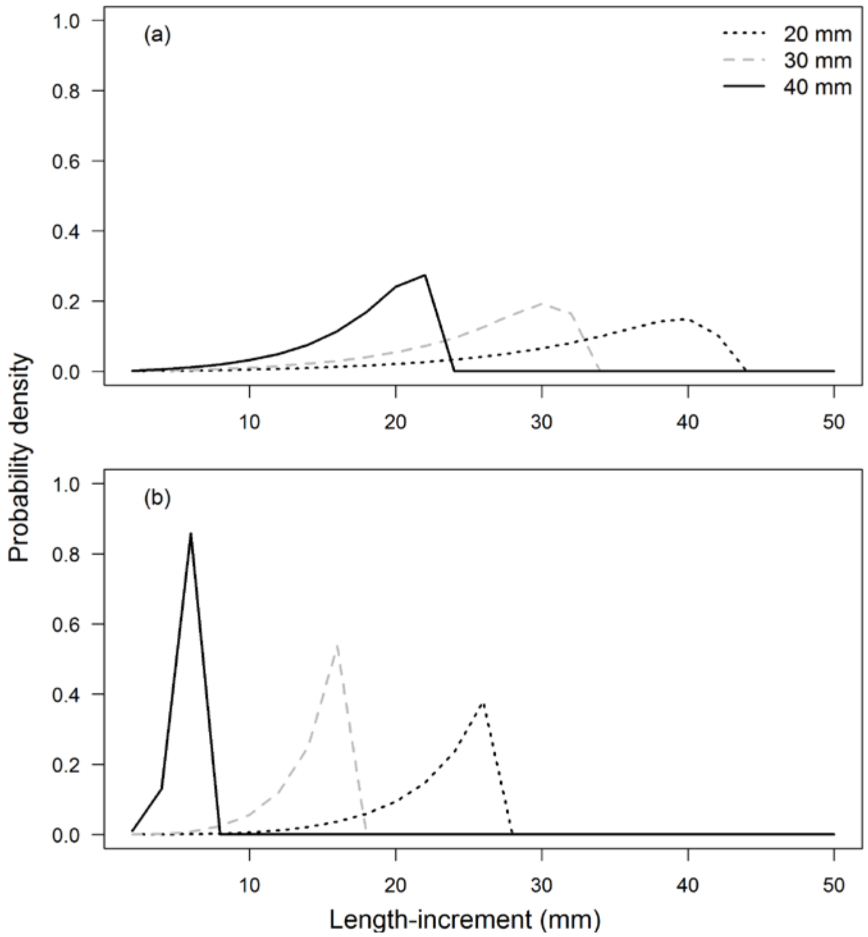


Figure 21-3. Probability density against length-increment (based on the k-Weibull model) of (a) female and (b) male Melicertus plebejus for a time interval of 1 year and initial sizes of 20, 30 and 40 mm.

21.5 DISCUSSION

Estimates produced by Lucas (1974) and Glaister *et al.* (1987) are based on fitting a deterministic VB–FGM to less representative samples. These authors used much smaller sample sizes, restricted to only parts of the species geographical distribution with the majority of recaptures occurring within 90–292 days of release. In contrast, our parameter estimates represent a summary of the growth characteristics across the full range of the species because they were determined from a much larger sample size that covers the bulk of the species distribution and includes recapture records at large for more than 1 year.

In this study, correction for the biasing effects of gear selectivity on parameter estimates was not attempted because size selectivity was assumed to be uniform. All tagged and released prawns were within the 100% retention area of the selection ogive for current fishing gear (Broadhurst *et al.* 2004). If the probability of recapture significantly increased with size, ignoring gear selectivity effects would lead to over-estimated growth parameters. In our study, parameter estimates were not affected by gear selectivity given that recaptured individuals in the different size classes had equal or very similar recapture probability.

Accounting for individual variability in growth is required when estimating growth parameters (Sainsbury 1980; Wang and Thomas 1995). The deterministic approach treats variation around the mean growth estimates as error whereas the stochastic approach captures individual growth variability which is represented by a distribution of size increments (Figure 21-3). Field observations support the stochastic model predictions; the L_∞ estimates for females and males are close to the maximum observed size: 73 mm C_L for females (Courtney *et al.* 1996) and 53 mm C_L for males (A. J. Courtney unpublished). Also, the distributions of size-increments are highly asymmetrical and have large variances (Figure 21-3); hence, average size-increments have very limited information about growth in a population. Therefore, a stochastic parameterization implies a more accurate description of growth and recruitment to the fishery in stock assessment models. The present study provided more representative growth estimates for M. plebejus across eastern Australia and captured the species natural growth heterogeneity, contributing with essential information for modelling the species population dynamics.

21.6 ACKNOWLEDGMENTS

This research was supported by the Queensland and Australian Governments through the Australian Fisheries Research and Development Corporation (FRDC 2008/019). We thank the commercial trawl fishers in Queensland and New South Wales who provided the information on recaptured tagged prawns.

22 Appendix 10. Linking spatial stock dynamics and economics: Evaluation of indicators and fishery management for the travelling eastern king prawn (*Melicertus plebejus*)

Michael F. O’Neill, George M. Leigh, You-Gan Wang, J. Matías Braccini, and Matthew C. Ives

Reduced economic circumstances have moved management goals towards higher profit, rather than maximum sustainable yields in several Australian fisheries. The eastern king prawn is one such fishery, for which we have developed new methodology for stock dynamics, calculation of model-based and data-based reference points and management strategy evaluation. The fishery is notable for the northward movement of prawns in eastern Australian waters, from the State jurisdiction of New South Wales to that of Queensland, as they grow to spawning size, so that vessels fishing in the northern deeper waters harvest more large prawns. Bio-economic fishing data were standardized for calibrating a length-structured spatial operating model. Model simulations identified that reduced boat numbers and fishing effort could improve profitability while retaining viable fishing in each jurisdiction. Simulations also identified catch-rate levels that were effective for monitoring in simple within-year effort-control rules. However, favourable performance of catch-rate indicators was achieved only when a meaningful upper limit was placed on total allowed fishing effort. The methods and findings will allow improved measures for monitoring fisheries and inform decision makers on the uncertainty and assumptions affecting economic indicators.

Keywords: Australia, catch rate standardisation, economic indicators, management strategy evaluation, prawns, spatial stock assessment

M. F. O’Neill: Agri-Science Queensland, Department of Agriculture, Fisheries and Forestry, Maroochy Research Facility, P.O. Box 5083 SCMC, Nambour, Queensland, 4560, Australia. M. F. O’Neill: School of Geographic Planning and Environmental Management, and Centre for Applications in Natural Resource Mathematics (CARM) in the School of Mathematics and Physics, The University of Queensland, Brisbane, 4072 Queensland, Australia. G. M. Leigh: Agri-Science Queensland, Department of Agriculture, Fisheries and Forestry, PO Box 6097, St Lucia, 4072 Queensland, Australia. Y.-G. Wang: Centre for Applications in Natural Resource Mathematics (CARM) in the School of Mathematics and Physics, The University of Queensland, Brisbane, 4072 Queensland, Australia. J. M. Braccini: Department of Fisheries, Fisheries and Marine Research Laboratories, PO Box 20 North Beach, 6920 Western Australia. M. C. Ives: Department of Primary Industries, Fisheries Research Centre, Cronulla, 2230 New South Wales, Australia. Correspondence to M. F. O’Neill: tel: +61 7 5453 5949; fax: +61 7 5453 5901; e-mail: michael.o’neill@daff.qld.gov.au.

22.1 Introduction

In many fisheries globally, challenging economic conditions have moved management agencies towards monitoring indicators for profit alongside traditional indicators for biological sustainability. The Australian eastern king prawn is one such fishery in which economic performance has only in recent years become a concern.

The eastern king prawn (EKP, *Melicertus plebejus* or *Penaeus plebejus*) is a major component of otter-trawl fishing along the east coast of Australia. The EKP is largely spatially separated from other target species, exists primarily in subtropical waters and extends across two jurisdictions belonging to the States of New South Wales (NSW) and Queensland (Figure 22-1). The otter-trawl fishery harvests about three thousand tonnes of EKP annually, with a landed value in excess of AUD$40 million. In addition to EKP, licensed vessels within each jurisdiction are free to direct their fishing effort towards other permitted species.

The jurisdictions currently manage their sectors independently using a range of input controls including limited vessel entry, boat-day/effort-unit allocations, vessel and gear size restrictions, and spatial-seasonal closures. Separate management regimes operate despite strong stock connectivity, whereby EKP travel large distances from New South Wales and inshore Queensland waters to deep waters (> 90m) off Queensland as individuals grow to spawning size (Braccini *et al.* 2012b; Lloyd-Jones *et al.* 2012; Montgomery *et al.* 2007). In 2010 about 600 vessels were licensed to fish EKP and other important Penaeid prawns and saucer scallop. Of these vessels, about 150 did not fish or harvest EKP. Spatially restricted licences were also granted to 24 New South Wales vessels to fish Queensland waters north to Fraser Island (Figure 21-1).

Even with the trawl fishery input controls, recent years of higher trawling costs and constant or falling product prices have reduced both profit and fishing effort (Figure 22-2). Over the whole mixed-species fishery, a substantial fraction of the fishing effort capacity may be economically unviable (Ives *et al.* 2013).

The reduced economic conditions have focused EKP industry and management on developing strategies to maximize economic performance, rather than promoting maximum sustainable yield (MSY) as suggested by an earlier evaluation of this fishery (O'Neill *et al.* 2005). These economic conditions influenced the Queensland 2010–2011 trawl management review of biological, economic and social objectives (Dichmont *et al.* 2013; Pascoe *et al.* 2013). In order to improve fishing profits, additional management measures were discussed, including further effort control and

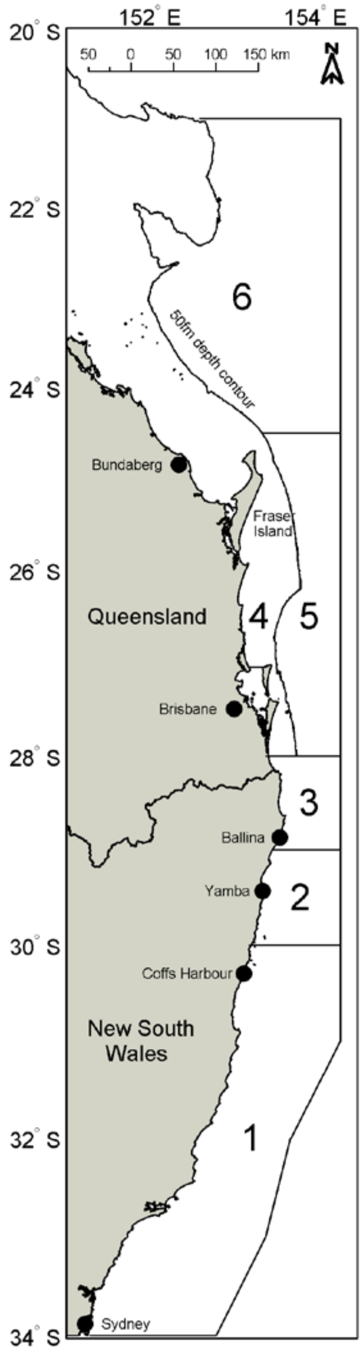


Figure 22-1. Map of the Australian eastern king prawn fishery zoned by analysis regions 1 to 6. Queensland region 4 covered water depths less than 50fm and excluded pre-oceanic-recruits from estuaries, Moreton Bay (adjacent to Brisbane) and Fraser Island north. Queensland regions 5 and 6 covered water depths equal to or greater than 50fm (≈90m). Management and fishing gear were not defined by water depths in New South Wales (regions 1 to 3); region 1 also included minor harvests taken south of Sydney to about 37°S.

seasonal closures with options for in-season management based on catch-rate reference points.

Fishing for EKP has fared better economically than other trawl species, and the EKP stock had experienced record levels of harvest in Queensland waters (Figure 22-2). This is partly due to the large size of mature EKP providing an export and domestic market niche over smaller prawn species. Also EKP fishing in Queensland occurs close to major markets and to saucer scallop (*Amusium balloti*) grounds that the same vessels can pulse-fish for some of the year. Finally, Queensland vessels may have benefited from recent declines in EKP harvest and fishing effort in New South Wales (Figure 22-2).

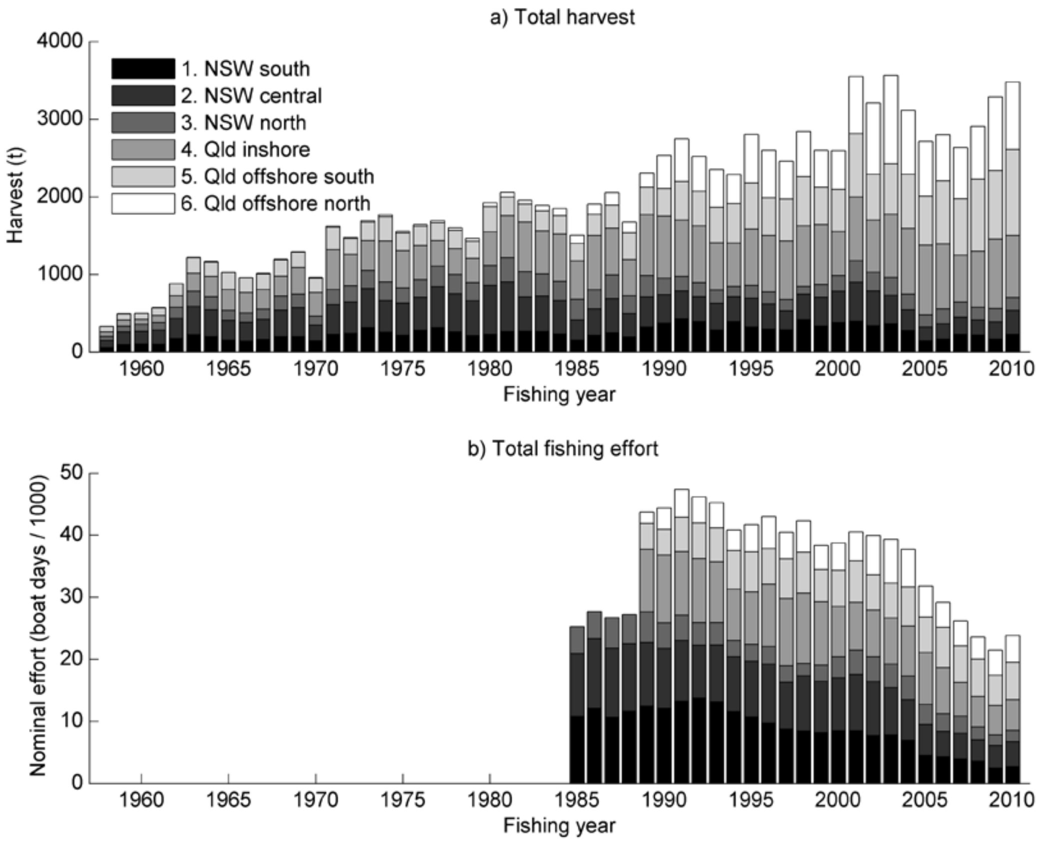


Figure 22-2. Summary fishery statistics for eastern king prawn a) harvest and b) fishing effort from New South Wales (NSW) and Queensland (Qld) waters. No records on total fishing effort were available before 1985 and 1989 fishing years from NSW and Qld respectively.

In this paper, in the light of current economic circumstances and record harvests, we apply both a length-structured spatial population model and an economic model to assess the fishing pressure, quantify economic performance and update reference points for the EKP fishery. We also use the models to evaluate stakeholder-suggested management procedures through simulation.

Reference points are key tools to indicate the state of a fishery. They can be based on measures such as catch rates or modelled stock biomasses. But their development is often complex, relying on numerical analyses and accurate data to index 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, which are data-based rather than model-based, have typically been used in prawn fisheries for status reporting and not management (Fisheries Queensland 2013; NSW Department of Primary Industries 2010). A notable exception was South Australia's Spencer Gulf Prawn Fishery, where fishery-independent survey catch rates were used to adaptively change spatial and seasonal closures to match resource availability (Dixon and Sloan 2007). For EKP, empirical catch-rate-limit reference points were implemented for status reporting in Queensland in 1999 (O'Neill *et al.* 2005) and in New South Wales in 2006 (NSW Department of Primary Industries 2006), but have not been validated and may be unrelated to sustainable stock levels or economics.

A reference-point policy of including vessel-based economics to calculate maximum economic yield (MEY) as a preferred objective to MSY was first introduced into Australian Government fisheries in 2007 (Australian Government 2007). This was applied to the Northern Prawn Fishery across tropical waters of the Northern Territory and the Gulf of Carpentaria (Punt *et al.* 2010).

The current study is the first to quantify empirical reference points for the combined New South Wales and Queensland EKP fishery, and the first to quantify economic indicators for the combined fishery. This study also demonstrates the benefits of model testing of indicators and reference points in fisheries science, and highlights important considerations for economic management.

22.2 METHODS

22.2.1 Commercial harvest data

Data were stratified by six fishing regions across New South Wales (NSW) and Queensland (Qld) State waters (Figure 22-1). From south to north the regions were defined and labelled as 1) NSW South (waters south of 30°S), 2) NSW Central (between 29°S and 30°S), 3) NSW North (between 28°S and 29°S), 4) Qld Inshore (< 50 fathom, approx. 90m, water depths, between 21°S and 28°S), 5) Qld Offshore South (>= 50fm water depths, between 24.5°S and 28°S), and 6) Qld Offshore North (>= 50fm water depths, between 21°S and 24.5°S latitude). Juveniles harvested from estuaries, Moreton Bay and Fraser Island north were excluded. Fishing years were defined and labelled from month November (1) to October (12).

Historical harvests of EKP date back to the early 1900's. Harvests were small (< 200 t) until the 1950's, and we assumed year 1958 to be the commencement of significant fishing mortality.

Monthly harvests from 1958 to 2010 were reconstructed from four data sources: 1) NSW monthly fisher catch returns from 1958 to 1983, 2) NSW monthly commercial logbooks from 1984 to 2010, 3) Queensland Fish Board annual records from 1958 to 1980, and 4) Queensland daily commercial logbooks 1988 to 2010.

NSW prawn harvest records from 1958 to 1978 aggregated species and regions. The proportion comprising EKP was separated based on information presented in Annual NSW Fisheries Reports with a base value of 20% given for the years from 1900 to 1957, and 42 %

observed in 1979. Hence, EKP was separated assuming a 1% annual increase starting from 21% in 1958 through to 41% in 1978. Regional harvests from 1958 to 1978 were disaggregated assuming an historical split of 29% for region 1, 47% for region 2 and 24% for region 3 based on the average for these regions between 1979 and 1989. All NSW regional EKP harvests were identifiable from 1979.

Queensland prawn harvests from 1958 to 1980 also aggregated species, but provided a spatial breakdown by fishing port. We used records from the port of Bundaberg south to the Queensland/NSW State border. The harvests were partitioned into species by removing Moreton Bay harvests (≈ 38% tonnage) and then assuming an EKP species proportion of 80%. From 1989 to 2010, Queensland EKP harvests were tallied from compulsory commercial logbooks. Missing records on total annual EKP harvest between 1981 and 1988 were estimated from log-linear regression using 1958 to 1980 and 1989 to 2010 annual estimates (adjusted R^2 = 0.86). Queensland EKP landings from 1958 to 1988 were expanded regionally and monthly based on Poisson generalized linear modelling of harvest patterns using 1989 to 1994 data. A log link was used on catch weight, and dispersion was estimated; the model terms were region × month + region × fishing year (adjusted R^2 = 0.64). Normal random uncertainty error of 0.26 (standard deviation implied from GLM analysis) was propagated monthly from 1958 to 1988.

22.2.2 Standardized commercial catch rates

Three catch rate analyses were conducted on New South Wales and Queensland logbook data (Table 22-1). Analyses 1 and 2 were for Queensland and analysis 3 for NSW. Analyses 1 and 3 were based on whole-fleet compulsory catch reports. Analysis 2 was on Queensland pre-1989 EKP catch rate data from voluntary logbook databases (O'Neill *et al.* 2005; O'Neill and Leigh 2006).

The analyses were linear mixed models (REML) with normally distributed errors on the log scale (GenStat 2011). They included both fixed ($\mathbf{X\beta}$) and random ($\mathbf{Z\gamma}$) terms, and followed the methods and terminology of O'Neill and Leigh (2007) and Braccini *et al.* (2012a). Where data $(\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3, \mathbf{X}_4, \mathbf{X}_5, \mathbf{Z}_1, \mathbf{Z}_2)$ were relevant and available, the models were fitted to estimate the following parameter effects:

- scalar model intercept β_0,
- abundance $\boldsymbol{\beta}_1$ for data $\mathbf{X}_1$ (three-way interaction, fishing year × month × region),
- vessel gear $\boldsymbol{\beta}_2$ for data $\mathbf{X}_2$ (log engine rated power, propeller nozzle, GPS, net type, log net length x region interaction, log mesh size, ground gear type, otter board type, BRDs and TEDs, and use of try-gear net.
- lunar phase $\boldsymbol{\beta}_3$ for data $\mathbf{X}_3$ (for luminance and luminance shifted ¼ phase),
- fishing effort $\boldsymbol{\beta}_4$ for data $\mathbf{X}_4$ (log hours for Queensland daily catches, log days for NSW monthly catches),
- by-catch $\boldsymbol{\beta}_5$ for data $\mathbf{X}_5$ (log of NSW school whiting catch + 0.001 kg),
- vessel efficiency random effects $\boldsymbol{\gamma}_1$ for vessel identifiers $\mathbf{Z}_1$, and
- location random effects $\boldsymbol{\gamma}_2$ for fishing logbook grid-square identifiers $\mathbf{Z}_2$.

Analysis 1 was completed with fishing power data $\mathbf{X_2}$ for $\boldsymbol{\beta}_2$. For analyses 2 and 3, the fishing power data $\mathbf{X_2}$ were not available. Therefore the $\boldsymbol{\beta}_2$ fishing power effect was not estimated but was inserted as an offset (Table 22-1). The offset was the estimated log fishing power $\boldsymbol{\beta}_2$ for deep and shallow water EKP from analysis 1, with linear trends hind cast for 1969 to 1988 (fishing power fixed terms only; Braccini *et al.* 2012a). Because NSW catches were reported monthly, no lunar $\boldsymbol{\beta}_3$ or location effects $\boldsymbol{\gamma}_2$ could be fitted in analysis 3. Also, the corresponding NSW school whiting (*Sillago robusta* and *S. flindersi*) catch effect was estimated to adjust for logbooks combining monthly effort for EKP and these alternative target species; this targeting/logbook effect was not present in Queensland waters (regions 4 to 6).

Table 22-1. Linear mixed models (REML) used to standardize catch rates from New South Wales (NSW) and Queensland (QLD).

Analysis 1	**QLD: regions 4 to 6 and years 1989 to 2010.**
Response:	$\log\left(\text{kgs boat-day}^{-1}\right)$
Fixed terms:	$\beta_0 + \mathbf{X}_1\boldsymbol{\beta}_1 + \mathbf{X}_2\boldsymbol{\beta}_2 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\beta_4$
Random terms:	$\mathbf{Z}_1\boldsymbol{\gamma}_1 + \mathbf{Z}_2\boldsymbol{\gamma}_2$
Offset:	—
Predictions:	$\boldsymbol{\beta}_1$
Analysis 2	**QLD: regions 4 to 6 and years 1969 to 1988.**
Response:	$\log\left(\text{kgs boat-day}^{-1}\right)$
Fixed terms:	$\beta_0 + \mathbf{X}_1\boldsymbol{\beta}_1 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\beta_4$
Random terms:	$\mathbf{Z}_1\boldsymbol{\gamma}_1 + \mathbf{Z}_2\boldsymbol{\gamma}_2$
Offset:	Backward linear extrapolation of deep and shallow water EKP log fishing power from $\boldsymbol{\beta}_2$ in analysis 1.
Predictions:	$\boldsymbol{\beta}_1$
Analysis 3	**NSW: regions 1 to 3 and years 1984 to 2010.**
Response:	$\log\left(\text{kgs boat-month}^{-1}\right)$
Fixed terms:	$\beta_0 + \mathbf{X}_1\boldsymbol{\beta}_1 + \mathbf{X}_4\beta_4 + \mathbf{X}_5\beta_5$
Random terms:	$\mathbf{Z}_1\boldsymbol{\gamma}_1$
Offset:	Combined deep and shallow water EKP log fishing power from $\boldsymbol{\beta}_2$ analysis 1, and 1984 – 1988 linearly hind casted.
Predictions:	$\boldsymbol{\beta}_1$

Standardized catch rates were predicted from the term $\boldsymbol{\beta}_1$, which provided a relative abundance estimate for each fishing year, month and region. No predictions were formed for missing month or region terms. The GenStat procedure “vpredict” was used to calculate monthly standardized catch rates equivalent to 2010 fleet fishing power in each region. For NSW catch rate analysis 3, predicted catch rates were scaled equivalent to when EKP was the primary target species landed. Queensland EKP analysis 2 standardized monthly catch rates were estimated only where 30 or more fishing days were recorded in a month and region; lower numbers of fishing records exhibited too much variability.

22.2.3 Standardized survey catch rates

Independent surveys of EKP recruitment abundance in region 4 were conducted in the fishing years 2000 and 2007–2010. The surveys monitored juvenile EKP catch rates in Moreton Bay and other prime coastal recruitment waters in Queensland. Between 200 and 300 beam trawl samples were conducted in each sampling year (Courtney *et al.* 2002; 2012; Fisheries Queensland 2007).

Individual beam trawl catches, measured in numbers of prawns, were analysed using a Poisson generalized linear model with log link and estimated dispersion (GenStat 2011; McCullagh and Nelder 1989). The explanatory factors were sampling area (two areas within Moreton Bay, plus three ocean areas), month (September to December) and fishing year. Within each sampling area, the trawl swept area changed very little over the fishing years; it was tested statistically, was non-significant and excluded from the model. The mean standardized catch between fishing years was used as a recruitment index.

22.2.4 Size composition data

Two data sets on size structure were used: 1) carapace length frequencies and 2) commercial size-grade frequencies. Together, these two data sets quantified regional and monthly changes in EKP size.

Carapace-length frequencies were recorded by scientists on board commercial fishing vessels. Each prawn was sexed and measured to 1 mm length classes. From NSW, summaries of monthly length frequencies were provided for a continuous 24 month period (1991–1992, regions 1 to 3). Length frequencies from Queensland waters were measured sporadically (region 4: November and December 1990, and October 2001; region 5: June and July 1993, and July 2002; region 6: January 2009).

Five vessels operating in Queensland waters provided at-sea EKP size grading data. The grading data were recorded between September 1997 and December 2008 from the deep northern waters of the fishery (region 6). The grading categories classified prawn sizes (number of prawns per pound; heads-on and sexes combined) which were sorted into 5kg boxes. In total, 136 monthly size-grade frequencies were tallied from 329,612 boxes and 10,947 boat-days of fishing. Size grade had seven categories: 1) > 30 $lb^{-1} \approx$ 1–27 mm carapace length, 2) 21–30 $lb^{-1} \approx$ 28–33 mm, 3) 16–20 $lb^{-1} \approx$ 34–37 mm, 4) 10–15 $lb^{-1} \approx$ 38–43 mm, 5) 8–10 $lb^{-1} \approx$ 44–47 mm, 6) 6–8 $lb^{-1} \approx$ 48–53 mm and 7) <6 $lb^{-1} \approx$ 54–75 mm. Soft and broken prawns, classified as an additional category, were infrequent and not analysed. No independent data were available to assess the accuracy of the at-sea commercial EKP 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. Similar prawn boxes (3 kg) have been validated as a reasonable measure for tiger prawn lengths in the Northern Prawn Fishery (O'Neill *et al.* 1999).

22.2.5 Economic data

The mean landing prices for EKP by size-grade were sourced from the NSW Sydney fish market and a Queensland processor representative. The price data were re-categorized by carapace length (Figure 22-3). The average by-product value per boat day by region (Table 22-2) was calculated using logbook harvests for the scyllarid lobsters, cephalopods and school whiting from New South Wales, and scyllarid lobsters, cephalopods, portunid crabs and saucer scallop from Queensland.

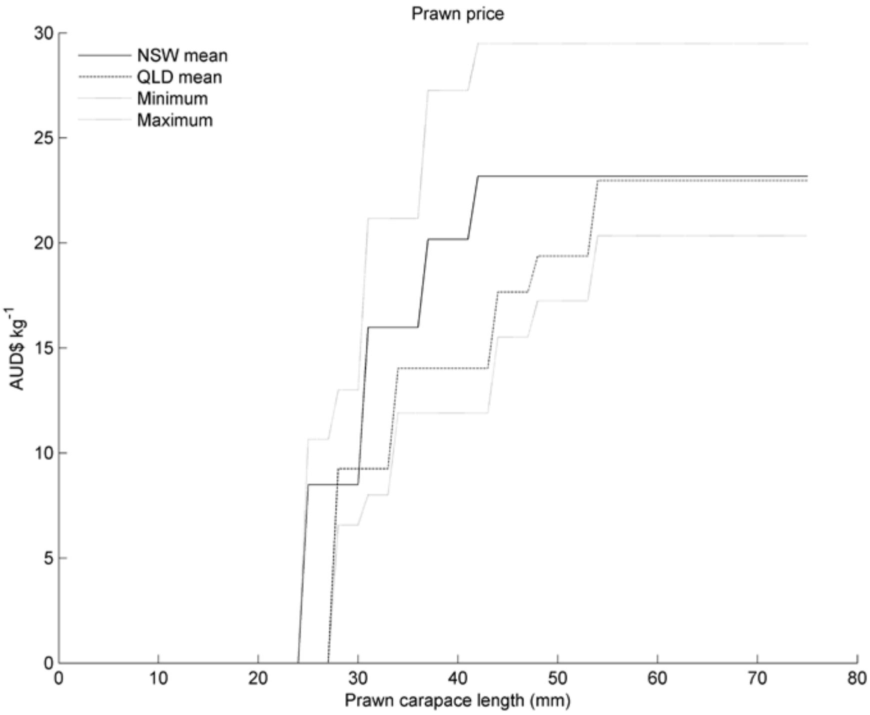


Figure 22-3. Mean eastern king prawn landing-prices (AUD\$ kg^{-1}) by prawn length and State. The minimum and maximum values indicate monthly variation, with higher prices around December and lower prices around June.

Vessel cost parameters (means and variances), other than fuel, were based on questionnaire responses from 24 vessel owners from the Queensland fishery (Table 22-2). The average fishing capacity of the vessels in the economic sample was very similar to the whole Queensland 2010 fleet as determined from vessel survey and logbook data (Braccini *et al.* 2012a; O'Neill and Leigh 2007). For example, the average vessel length was 17.0 m for the sample vs 17.5m for the Queensland fleet. Average costs in NSW were adjusted for the smaller average vessel size there.

Queensland fuel cost (c_F) means and variances were calculated using 2010 regional fuel use data (Braccini *et al.* 2012a; O'Neill and Leigh 2007) and average net diesel fuel price paid after subsidies of \$0.85 litre^{-1} (ABARES 2011). Fuel costs (c_F) for New South Wales were based on Queensland inshore vessels (region 4), again adjusted down for the smaller average vessel size in NSW.

Table 22-2. Input parameter values and their 95% confidence intervals for the economic model.

Parameters		New South Wales		Queensland
Variable costs:				
Labour (c_L: proportion of catch $)		0.29 (0.2 : 0.39)		0.29 (0.2 : 0.39)
Packaging (c_M: \$ kg^{-1})		0.41 (0.28 : 0.54)		0.41 (0.28 : 0.54)
Repairs (c_K: \$ boat-day^{-1})		288.63 (201.26 : 415.74)		407.46 (320.82 : 520.1)
Fuel (c_F: \$ boat-day^{-1})	Reg. 1	526.79 (476.8 : 576.37)	Reg. 4	546.35 (494.58 : 597.76)
Fuel (c_F: \$ boat-day^{-1})	Reg. 2	526.4 (476.99 : 575.11)	Reg. 5	563.1 (512.04 : 615.42)
Fuel (c_F: \$ boat-day^{-1})	Reg. 3	526.11 (477 : 576.45)	Reg. 6	760.19 (708.98 : 812.81)
Incidentals (c_O: \$ boat-day^{-1})		44.26 (22.98 : 65.98)		44.26 (22.98 : 65.98)
Annual fixed costs:				
Vessel costs (W_y: \$ boat^{-1})		28637 (23608 : 34769)		46170 (39403 : 53998)
Total investment (K_y: \$ boat^{-1})		255330 (191910 : 338710)		673590 (551810 : 817980)
Proportion allocated to EKP (ρ)		0.5 (0.4 : 0.6)		0.67 (0.57 : 0.76)
Revenue from by-product:				
Catch value ($\overline{B}_r^{by}$: \$ boat-day^{-1})	Reg. 1	195.91 (182.15 : 209.65)	Reg. 4	221.89 (86.7 : 349.14)
	Reg. 2	211.42 (177.06 : 244.26)	Reg. 5	122.26 (52.08 : 192.01)
	Reg. 3	112.87 (100.99 : 124.95)	Reg. 6	62.91 (2.73 : 122.84)
Annual fishing effort:				
Mean number of days boat-year^{-1} $(\bar{d})$		42 (33 : 52)		74 (66 : 83)
Annual economic rates:				
Interest rate (i)		0.05 (0.034 : 0.072)		0.05 (0.034 : 0.072)
Opportunity cost (o) = i				
Depreciation rate (d)*		0.02 (0.02 : 0.037)		0.02 (0.02 : 0.037)

* Uniform variation was assumed between lower and upper confidence intervals.

22.2.6 Operating model

The population dynamic model had a monthly time step and tracked numbers (N) and biomass (B) of prawns by their sex (s), length (l) and spatial region (r) (Table 22-3; Table 22-4), and included the processes of mortality, growth, movement and recruitment in every month (t). The model was run in two phases: (i) historical estimation of the EKP stock from 1958 to 2010 and (ii) simulations of EKP parameter values and uncertainty to evaluate reference points and management procedures.

Model parameters were estimated by calibrating the model to regional standardized catch rates and size-composition data (Table 22-5). Primary importance was placed on fitting the standardized catch rates (Francis 2011). Effective sample sizes for scaling multinomial likelihoods were calculated within the model in order to give realistic weighting to the size composition data. Due to the relatively uninformative (flat) annual trend in EKP catch rates from NSW (regions 1 to 3), a penalty function was included to prevent unrealistically large population estimates and low estimates of harvest rate. Likelihood functions were also used for stock-recruitment steepness (h), natural mortality (M) and annual recruitment variation (η) (Table 22-6). The estimation process was conducted in Matlab® (MathWorks 2013), and consisted of a maximum likelihood step followed by Markov Chain Monte Carlo sampling (MCMC). The MCMC used a multivariate vector-jumping Metropolis-Hastings algorithm described by Gelman *et al.* (2004), with 110,000 samples run to estimate the parameter covariance matrix and customize the vector jumping to ensure acceptance ratios of about 0.2

(Roberts *et al.* 1997). A further two million samples were run with fixed covariance. Parameter distributions were based on 1000 posterior samples thinned from the last two million simulations. The “coda” package of the software *R* was used to analyse and confirm MCMC convergence (Plummer *et al.* 2006).

Table 22-3. Equations used for simulating EKP population dynamics (for notation, Table 22-4).

Monthly population dynamics	**Equations**
Number of prawns:	
$N_{l,r,t,s} = \exp(-M)\sum_{r'} \mathrm{T}_{r,r',t-1} \sum_{l'} \Xi_{l,l',r',t-1,s}\left(1-v_{l',r'}u_{r',t-1}\right)N_{l',r',t-1,s} + 0.5R_{l,r,t}$	(1)
Recruitment number — Beverton-Holt formulation:	
$R_{l,r,t} = \dfrac{E_{y-1}}{\alpha_r + \beta_r E_{y-1}}\exp(\eta_y)\phi_{r,t}\Lambda_l$, where y indicated the fishing year.	(2)
Spawning index — annual number of eggs:	
$E_y = \sum_t \sum_r \sum_l N_{l,r,t,s} m_{l,r} f_l \theta_r$	(3)
Recruitment pattern — normalized monthly proportion:	
$\phi_{r,t} = \exp\left[\kappa\cos\{2\pi(t-\mu)/12\}\right] \Big/ \sum_{t'=1}^{12}\exp\left[\kappa\cos\{2\pi(t'-\mu)/12\}\right]$, where *t* indicated time-of-year months 1…12.	(4)
Mid-month exploitable biomasses—forms 1 and 2:	
$B^1_{r,t} = \sum_l \sum_s N_{l,r,t,s} w_{l,s} v_{l,r} \exp(-M/2)$ $B^2_{r,t} = \sum_l \sum_s N_{l,r,t,s} w_{l,s} v_{l,r} \exp(-M/2)(1-u_{r,t}/2)$	(5)
Harvest rate:	
$u_{r,t} = C_{r,t} \big/ B^1_{r,t}$, where *C* was a regions monthly harvest kgs.	(6)
Prawn vulnerability to fishing:	
$v_{l,r} = \dfrac{1}{1+\exp\left(\delta\left(l^{50}_r - l\right)\right)}$	(7)
Fishery data indicators—catch rates:	
Fishery (f; kg boat-day^{-1}): $c^{\mathrm{f}}_{r,t} = q^{\mathrm{f}}_r(t) B_{r,t} \exp\left(\varepsilon^{\mathrm{f}}_{r,t}\right)$ Survey (s; number trawl-shot^{-1}): $c^{\mathrm{s}}_{r=4,y} = q^{\mathrm{s}}_4 \overline{R}_{4,y(1,2)} \exp(-M/2)\exp\left(\varepsilon^{\mathrm{s}}_{4,y}\right)$ for r=4, fishing months = Oct(1) and Nov(2)	(8)

Table 22-4. Definitions and values for the population model parameters.

Model parameters	Equations, values and errors	Notes
Assumed		The values and errors were calculated from published research or data.
T	$p_{4\rightarrow6} = p_{4\rightarrow5}\dfrac{\exp(\rho)}{1+\exp(\rho)}$, where ρ was an estimated logit variable.	Transition probability matrix (6x6) for moving EKP between regions $r' \rightarrow r$. The matrix was calculated by aggregating finer scale probabilities to produce an approximate Markov process at the larger region scale (Braccini *et al.* 2012b). Tag-recapture data was too limited to quantify northern EKP transitions from region 4 to 6. This probability was estimated to be proportional to the region 4 to 5 transition. Twelve matrices were used to vary movement by time-month *t*.
Ξ	$\text{lat} = [-32.0, -29.5, -28.5, -26.5, -26.5, -23]$ $\sigma_{\text{male}} = 2.069; \sigma_{\text{female}} = 2.277$	Growth transition matrix allocated a proportion of EKP in carapace length-class l' at time *t*-1 to grow into a new length l over one time-month *t*. The transitions varied with prawn sex *s*, region *r* and month *t*, and assumed a normal probability density function (O'Neill *et al.* 2010; Punt *et al.* 2010; Sadovy *et al.* 2007). The growth model was based on the latitudinal and seasonal estimates of EKP (Lloyd-Jones *et al.* 2012). Their *k* and θ_1 parameters were rescaled per degree of latitude and month. The parameter "lat" specified the degree latitude for each region and σ were the standard deviations of the monthly growth increment, in mm.
Λ	Summary percentiles [2.5 25 50 75 97.5] = 13, 18, 22, 27 and 35 mm.	Proportion of EKP recruitment in length class l (1…75 mm). The proportions were calculated from a lognormal distribution for length at recruitment, based on region 4 monitoring data in fishing years 2000 and 2007 to 2010. The frequencies were approximately equal for male and female EKP (Courtney *et al.* 2002).
w	$w_{l,s} = a_s l^{b_s} / 1000$, $a_{\text{male}} = 0.0017, b_{\text{male}} = 2.7005$, $a_{\text{female}} = 0.0021, b_{\text{female}} = 2.6333$	Average EKP weight (kg) at length l for sex *s* (Courtney 1997).
f	$f_l = 10^{(al+b)}$ $a = 0.0199; b = 4.7528$	Fecundity (egg production) at length per female EKP (Courtney 1997; Montgomery *et al.* 2007).
m	Summary of maturity schedule: $l_{50} = 38; l_{95} = 45 \quad \text{for} \quad r = 3,5,6$ $l_{50} = 40; l_{95} = 45 \quad \text{for} \quad r = 1,2,4$	Logistic maturity schedule by carapace length (mm) and region. The schedule was estimated using binomial regression and logit link, m ~ Constant + Year + Month + Region/Length; adjusted R^2 = 0.746. The GenStat model terms Year, Month and Region were factors, while Length was a variate.
θ	θ =[0.15, 0.33, 0.6, 0.6, 0.6, 0.75]	Proportion of EKP spawning by region (Montgomery *et al.* 2007).

Table 22.4 Continued.

Model parameters	Equations, values and errors	Notes
Estimated	N=76	The values and their variances and covariance's were estimated.
ξ and Υ_r	$\alpha_r = E_0\left(1-h\right)/\left(4hR_{0,r}\right)$ $\beta_r = \left(5h-1\right)/\left(4hR_{0,r}\right)$ $R_{0,r} = \exp(\Upsilon_r)\times 10^8$ $h = \exp\left(\xi\right)/1+\exp\left(\xi\right)$	Five parameters for the Beverton-Holt spawner-recruitment equation 2 (Table 22-3), that defined α and β (Haddon 2001). Virgin recruitment (R_0) was estimated on the log scale separately for regions 1 to 4 in 1958. One estimated logit value of steepness (h) was assumed for the EKP stock, according to log-likelihood equation 12 (Table 22-6). E_0 was the calculated overall virgin egg production.
μ and κ	μ_r for each region 1 to 4. κ_1 for regions 1 to 3 (New South Wales). κ_2 for region 4 (Queensland).	Six parameters for the estimated mode (μ) and concentration (κ) of the monthly (time-months 1…12) recruitment patterns, equation 4 (Table 22-3); according to a von Mises directional distribution (Mardia and Jupp 2000).
l^{50} and δ	l_1^{50} for region 1. l_2^{50} for regions 2 to 4. l_3^{50} for regions 5 and 6.	Four parameters for the estimated logistic vulnerability, equation 7 (Table 22-3). δ governed the initial steepness of the curve and l^{50} was the length at 50% selection by region.
M	Normal prior distribution	One parameter for instantaneous natural mortality month^{-1}, according to log-likelihood equation 13 (Table 22-6). The prior distribution allowed for two to three years longevity (Lloyd-Jones *et al.* 2012), and values around those used in previous EKP modelling (Lucas 1974; O'Neill *et al.* 2005). Ives and Scandol (2007) summarized estimates of EKP M ranging from 0.13 to 0.35, with values ≥ 0.24 possibly biased upwards (Glaister *et al.* 1990).
ρ	See variable T	One parameter for calculating EKP movement from region 4 to 6.

ζ	$\boldsymbol{\eta} = \boldsymbol{\zeta}\mathbf{e}$
	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 14 (Table 22-6. ζ were the 52 estimated parameters known as barycentric or simplex coordinates, distributed $NID\left(0,\sigma\right)$ with number nparRresid = number of recruitment years – 1 (Möbius 1827; Sklyarenko 2011). **e** was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill *et al.* 2011).

$q_r^{\mathrm{f}}\left(t\right)$ and	$q_r^{\mathrm{f}}\left(t\right) = \exp\left(\log\left(q_r^{\mathrm{f}}\right) - \varsigma\left(\cos\left(t\right) + \vartheta_r \sin\left(t\right)\right)/\sqrt{1+\vartheta_r^2}\right)$ $t = 2\pi\,\mathrm{seqmonth}/12$	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. The equation

q_4^s	controlled the amplitude (ς) of catchability across regions, but allowed for different peaks (ϑ_r) (7 parameters estimated). The equation was divided by a square root term to ensure the parameters were not periodic. Each region's overall catchability q_r^f was calculated as closed-form mean estimates of standardized catch rates divided by the mid-month biomass form2 (Table 22-3) (Haddon 2001). Survey catchability was a single closed-form mean of standardized survey catch rates divided by region 4 recruitment adjusted by $\exp(-M/2)$.

Table 22-5.Negative log-likelihood functions for calibrating population dynamics.

-*LL* functions for:	**Theory description**	**Equations**
Log standardized catch rates (c^{f} or c^{s}): $\frac{n}{2}\left(\log(2\pi)+2\log(\hat{\sigma})+1\right)$, 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) and box-grading (g) size-composition data: $-\sum\left(\log\left(\nu^{(\tilde{n}-1)/2}\right)-\left(\frac{1}{2}(\tilde{n}-1)\frac{\nu}{\hat{\nu}}\right)\right)$, or simplified as $-\sum\frac{1}{2}(\tilde{n}-1)(\log\nu-\nu/\hat{\nu})$, where $\tilde{n}$ was the total number of size categories (l or g) with proportion-frequency > 0, $\hat{\nu}=(\tilde{n}-1)/2\sum\hat{p}\log(\hat{p}/p)$, $\nu=\max(2,\hat{\nu})$ specified sample size bounds, $\hat{p}$ were the observed proportions > 0 and p were predicted.	Effective sample size (ν) in multinomial likelihoods (Leigh 2011; O'Neill *et al.* 2011)	(10)
Preventing unrealistically large population estimates and low estimates of harvest rate: $0.5\left(\frac{\tilde{u}-\max\left(CN_y/R_y\right)}{\sigma}\right)^2 b$, where $\tilde{u}$ was the minimum annual harvest fraction 0.2, σ was the user defined std for penalty weighting (0.005), CN_y was the annual total number of EKP caught over the regions, R_y the annual recruitment, and b was a logical switch for $\max\left(CN_y/R_y\right)<\tilde{u}$. The penalty was applied between 1992 and 2010.	Optimisation penalty (Hall and Watson 2000)	(11)

Table 22-6. Negative log-likelihood functions for parameter bounds and distributions.

-*LL* functions for:	Equation
Stock recruitment steepness h **:**	
$0.5\left(\frac{\operatorname{logit}(h)-\operatorname{logit}(0.5)}{\sigma}\right)^2$, where $\sigma = 0.7$ defined a broad prior distribution.	(12)
Instantaneous natural mortality M **month**[-1]**:**	
$0.5\left(\frac{M-0.2}{\sigma}\right)^2$, where $\sigma = 0.05$ defined the prior distribution ≅ 28% CV.	(13)
Annual log recruitment deviates η_y **:**	
$\frac{n}{2}\left(\log(2\pi)+2\log(\sigma)+(\hat{\sigma}/\sigma)^2\right)$, or simplified as $n\left(\log\sigma+\frac{1}{2}(\hat{\sigma}/\sigma)^2\right)$, where $\sigma=\min\left(\max(\hat{\sigma},\sigma_{\min}),\sigma_{\max}\right)$, $\sigma_{\min}=0.1$ and $\sigma_{\max}=0.4$ specified bounds, $\hat{\sigma}=\sqrt{\sum\eta_y{}^2/n}$ and n was the number of recruitment years y.	(14)

22.2.7 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:

$$\text{NPV} = \sum_{y=1}^{\infty} a^y \pi_y$$

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:

$$\text{NPV} = \sum_{y=1}^{T-1} a^y \pi_y + a^{T-1} i^{-1} \pi_T .$$

This NPV function differs from formula (13) of Punt *et al.* (2010), in that we have 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:

$$\pi_y = \sum_r \left(\sum_t \left(\sum_l v_{r,t,l} C_{r,t,l} - \Omega^{\text{V}}_{r,t} \right) + \overline{B}^{by}_r (1-c_L) E_{r,y} - \left(\Omega^{\text{F}}_{r,y} \frac{E_{r,y}}{\overline{d}_r} \rho \right) \right),$$

where $v_{r,l,t}$ was the average price received by fishers for EKP in region *r*, time-month *t* and length class *l* (Figure 22-3), $C_{r,t,l}$ was the EKP harvest weight, $\Omega^{\text{V}}_{r,t}$ was the total variable costs, $\overline{B}^{by}_r$ 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), $E_{r,y}$ was the total annual boat days fished, $\Omega^{\mathrm{F}}_{r,y}$ the average annual fixed costs, $\bar{d}_r$ was the mean number of days fished per boat year and ρ was the fraction of fixed costs allocated to the EKP fishery (Table 22-2). The division by $\bar{d}_r$ allowed the annual number of vessels to change based on profitability.

Variable costs $\Omega^{\mathrm{V}}_{r,t}$ were calculated by region *r* and 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 22-2):

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

Average annual fixed costs $\Omega^{\mathrm{F}}_{r,y}$ were calculated using regional vessel costs (W_r), and opportunity (*o*) and depreciation (*d*) rates on average total investment value per vessel ($K_{r,y}$) (Table 22-2):

$$\Omega^{\mathrm{F}}_{r,y} = \left(W_r + (o+d)K_{r,y}\right).$$

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

22.2.8 Simulation and management procedures

Model simulations were used to estimate management reference points and evaluate proposed management procedures. The simulations were driven by forward projection methodology similar to Richards *et al.* (1998). To drive the simulations from 2011 to 2020, 1000 multivariate length-spatial parameter estimates were created from the MCMC covariance matrix. For economics, 1000 random variations on Table 22-2 were generated based on each variable’s variance. The parameters were used to simulate future uncertainties, including stochastic recruitment.

Equilibrium reference points for MSY and MEY were calculated by optimizing 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 mortality rates and monthly fishing pattern calculated from data from the five years 2006–2010.

Nine management procedures were developed by consultation with fishery managers and stakeholders (Table 22-7). They utilized one-month trawl closures, a cap on total fishing effort, and within-year catch-rate control rules. Management procedures 1 to 4 represented status quo total fishing effort and compared alternative one-month regional EKP closures. Procedure 5 contrasted procedure 4 with reduced total fishing effort at $E_{\mathrm{MEYfv}}(\bar{d})$. Procedures 6 to 9 used regional MSY and $\mathrm{MEY_v}$ catch rate control rules to manage total fishing efforts of E_{MSY} and $E_{\mathrm{MEYfv}}(\bar{d})$.

In addition, the management procedures were replicated in two scenarios: A) 1 to 9 under 2010 fishing costs and fishing power, and B) 10 to 18 under 3% p.a. increased costs and power. In total, 18 cases were simulated (nine management procedures by two economic scenarios) to assess management performance over ten years. Each case was evaluated using six performance measures grouped into three pairs: (i) industry functioning: average annual harvest and effort; (ii) economics: relative net present value (NPV) and average catch rates; and (iii) 2020 population status: spawning egg production and exploitable biomass. The NPV calculated over all future years was used in order to record a long term benefit for fishing EKP after 10 years, whereas the other performance measures were averaged over 10 years to provide a shorter-term perspective.

Table 22-7. Eastern king prawn management procedures developed by consultation and simulated over ten future years.

Management brief	**Management procedures**		
	Total effort (max boat days)	**Regions closed**	**Month closed (month number)**
1. Status quo.	Max last five years, $\sum \approx 30000$	Qld (area 4)	Oct (12)
2. Close NSW southern and Qld inshore waters in January.	Max last five years, $\sum \approx 30000$	NSW (area 1) Qld (area 4)	Jan (3)
3. Close Qld waters in January.	Max last five years, $\sum \approx 30000$	Qld waters (areas 4 to 6)	Jan (3)
4. Close all NSW and Qld waters in January.	Max last five years, $\sum \approx 30000$	All waters (areas 1 to 6)	Jan (3)
5. Limit total effort to E_{MEYfv}, and close all waters in January.	$E_{MEYfv} \approx 8000$	All waters (areas 1 to 6)	Jan (3)
6. Limit total effort to E_{MSY}, and close regional waters on MSY catch rate thresholds.	$E_{MSY} \approx 38000$	Variable m_r to Oct (12)	
7. Limit total effort to E_{MEYfv} and close regional waters on MSY catch rate thresholds.	$E_{MEYfv} \approx 8000$	Variable m_r to Oct (12)	
8. Limit total effort to E_{MSY}, and close regional waters on MEY_v catch rate thresholds.	$E_{MSY} \approx 38000$	Variable m_r to Oct (12)	
9. Limit total effort to E_{MEYfv} and close regional waters on MEY_v catch rate thresholds.	$E_{MEYfv} \approx 8000$	Variable m_r to Oct (12)	

For management procedures 6 to 9 (Table 22-7), closures for different areas were calculated based on catch rate thresholds:

$$m_r = \text{firstmonth}\left(c_{r,m}^{f} < c_{r,m}^{limit}\right) + 1,$$

where $c_{r,m}^{f}$ was the fishery standardized catch rate (kgs) for region r and month m, $cr_{r,m}^{limit}$ was the standardized catch rate reference point for either MSY or MEY_v, and +1 month provided industry time to prepare for area shut down. The first two months of the fishing year, November and December, were always open.

Simulated total fishing effort was split across regions and months based on historical patterns. A beta distribution was assumed for variation and implementation error below maximum

$E_{status\text{-}quo}$ and E_{MSY} total fishing efforts; based on the ratio of 2006–2010 fishing effort to $E_{status\text{-}quo}$. If a region was closed to fishing, a proportion of that fishing effort was reallocated to other regions based on probabilities calculated from logbook tallies of each vessel's regional pattern of fishing.

22.3 RESULTS

22.3.1 Model calibration and description

The length-spatial model predicted that historical EKP spawning egg production and exploitable biomass, expressed as a median ratio relative to 1958, had declined roughly 40–50% up to 1985 and remained steady through to 2006. The median ratios had increased since 2006 and in 2010 were 60–80% of 1958 levels.

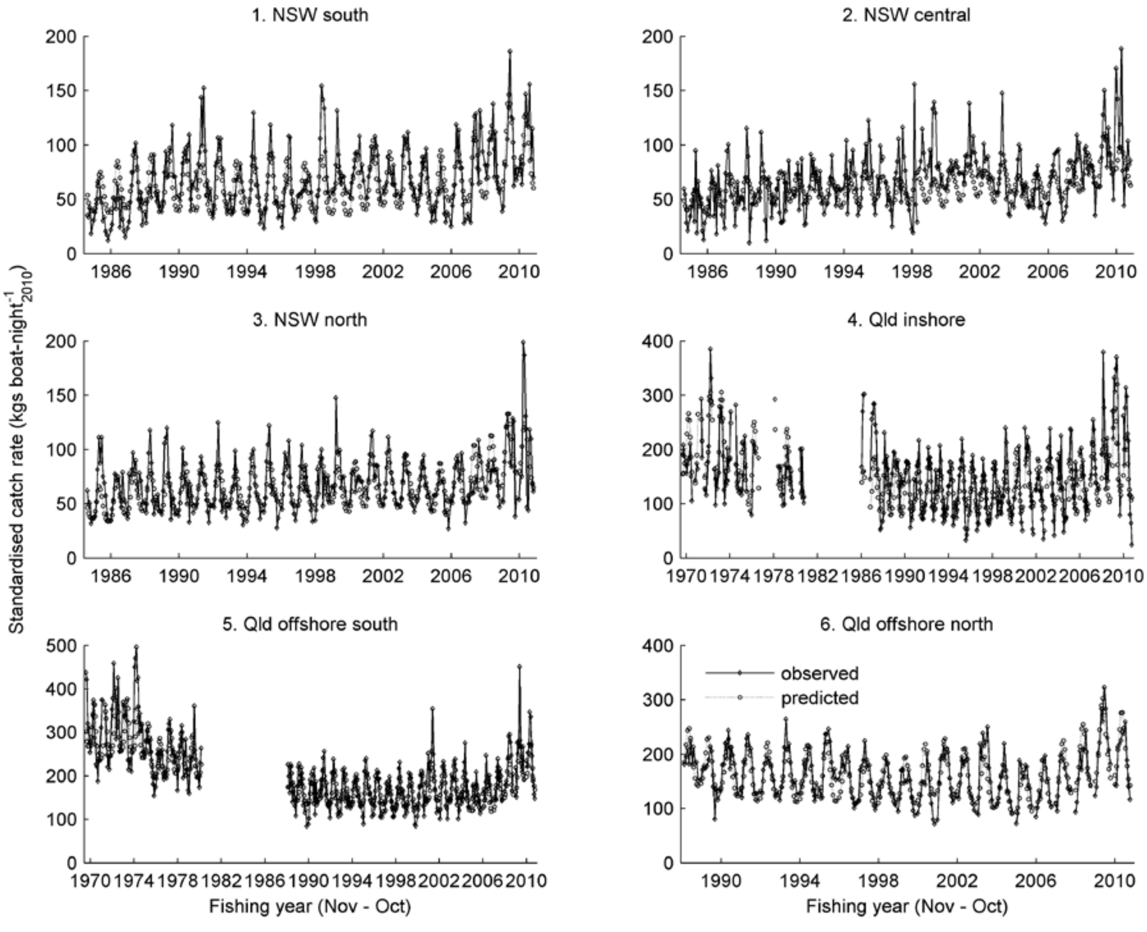


Figure 22-4. Eastern king prawn observed (standardised) and model predicted catch rates for each spatial region and month.

The model fitted the EKP fishery standardized catch rates relatively well, although region 2 EKP catch rates were less seasonal and less predictable (Figure 22-4). Standard deviations of log-residuals were 0.34, 0.39, 0.24, 0.33, 0.18, and 0.16 for regions 1 to 6 respectively; they were larger in NSW compared to Queensland, and region 4 deviations were inflated by the more variable pre-1989 catch rates from voluntary logbook records. Model calibrations were not influenced by the region 4 EKP recruitment indices due to the limited 5-year time series (standard deviation of log-residuals = 0.21). Estimated effective sample sizes for the length- and grading-frequency data were typical for fisheries data (Pennington and Vølstad 1994), and indicated that prawns within the samples were correlated, not necessarily that the model didn't fit the data (Figure 22-5 and Figure 22-6). For region 6 where large EKP were caught, the model predicted the grading data very well (Figure 22-6).

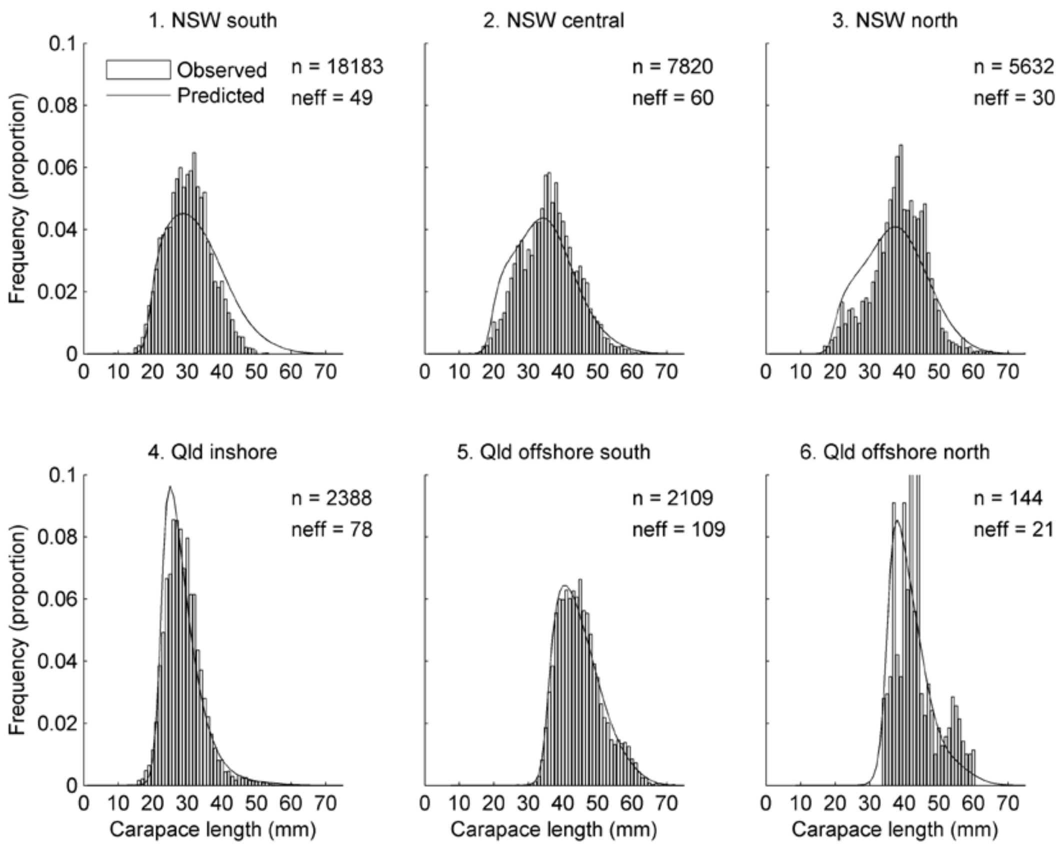


Figure 22-5. Eastern king prawn observed and model predicted harvest length frequencies for each region. The plot frequencies were summed over sexes and by effective sample numbers for the months with available data. Mean number of prawns measured (n) and effective numbers (neff) per sex and month are shown.

Roughly 56% of EKP recruitment to the fishery was estimated to enter region 4, 13% in region 1 and 30% in region 2, with little recruitment occurring in region 3 (Table 22-8). Recruitment steepness was calibrated at 0.36. Typical recruitment modes were estimated in February, December, October and December for regions 1 to 4 respectively. No large yearly variation in catch rates was evident and annual log recruitment standard deviation was estimated at 0.12. EKP mean carapace length at 50% vulnerability was 21mm in region 1, 25mm in regions 2 to 4 and 35mm in regions 5 and 6. Instantaneous natural mortality was calibrated to 0.184 month^{-1}.

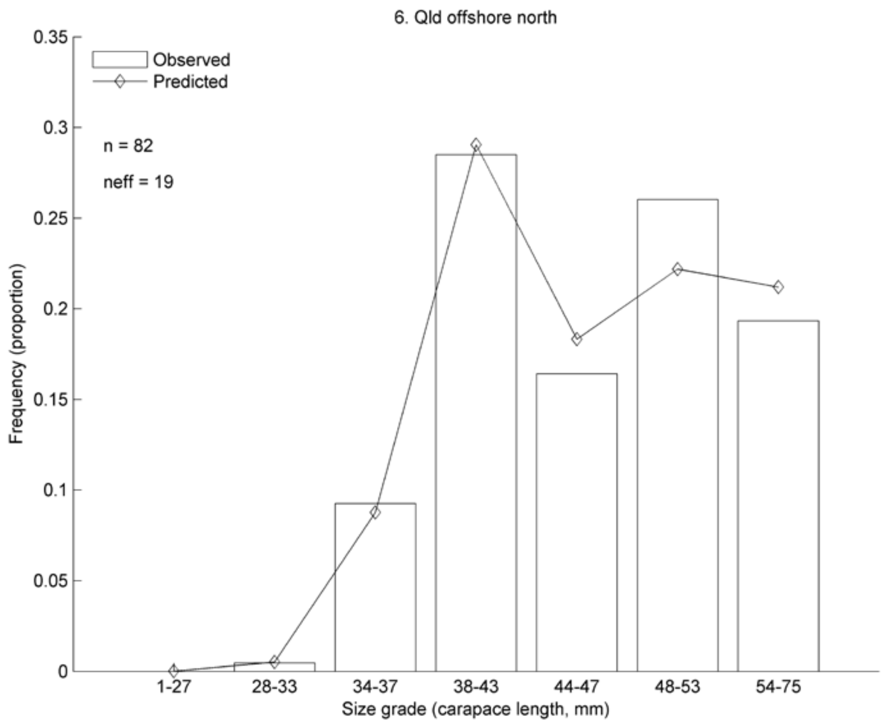


Figure 22-6. Eastern king prawn observed and model predicted frequencies of harvest size grading data from Queensland offshore north waters (region 6). The plot frequencies were summed by effective sample numbers over 136 monthly prawn-size-box frequencies. Mean sample number of 5kg boxes graded (n) and effective numbers (neff) per month shown.

Catchability was estimated to peak in January with a low in July for regions 1, 3, 5 and 6. Region 4 catchability peaked in March, with a low in September. The regional amplitude in catchability in these regions was estimated at 20%. Region 2 catchability was less seasonal.

Reference points for maximum sustainable yield (MSY) and maximum economic yield (MEY) are presented in Table 22-9. The MEY results were highly dependent on the specified economic parameters, listed in Table 22-2. The variability in MEY was tabulated for the average number of days currently fished per boat per year ($\bar{d}$, Table 22-2), twice this number ($2\bar{d}$) and for variable costs only (Table 22-9). The level $2\bar{d}$ was included as a relevant illustration for potential effort per boat if the fleet vessel numbers were reduced to allow each vessel much higher fishing capacity. The MEY effort estimates ranged between 7000 and 20,000 boat days; the lower estimates were applicable for lower values of $\bar{d}$, and higher fishing costs and power. Fishing effort in 2010 was about 24,000 boat days.

Mean catch rate reference points, corresponding to MSY and MEY, are plotted in Figure 22-7. Two versions of MEY catch rates were calculated: one maximized fishing profit against variable costs only (labelled as MEY_v), while the other maximized against both variable and fixed costs (labelled MEY_{vf} and dependent on $\bar{d}$). These reference points were used as catch rate thresholds for simulating management procedures 6 to 9. Retrospectively, the catch rate reference points suggested consistent profitable catch rates in the last three years 2008–2010 across all regions.

Table 22-8. Parameter estimates and standard errors for the model calibration $\left(-\log l = -3253.7; \sigma_r = 0.115\right)$.

Parameter	**Estimate**	**Standard error**	**Estimate transformed**
ξ	-0.568	0.089	0.362
Υ_1	0.289	0.206	1.335
Υ_2	1.171	0.103	3.225
Υ_3	-2.713	0.48	0.066
Υ_4	1.772	0.083	5.884
μ_1	4.361	0.141	4.361
μ_2	1.918	0.153	1.918
μ_3	-1.165	0.259	-1.165
μ_4	1.949	0.112	1.949
$\kappa_{1\ldots3}$	1.573	0.132	1.573
κ_4	0.819	0.071	0.819
l_1^{50}	20.671	0.661	20.671
$l_{2\ldots4}^{50}$	24.483	0.731	24.483
$l_{5\ldots6}^{50}$	35.551	0.193	35.551
δ	0.921	0.027	0.921
M	0.184	0.005	0.184
ρ	0.939	0.281	0.719
ς	0.196	0.012	0.196
ϑ_1	-0.455	0.279	-0.455
ϑ_2	1.261	0.236	1.261
ϑ_3	-0.876	0.273	-0.876
ϑ_4	0.521	0.307	0.521
ϑ_5	-0.800	0.137	-0.800
ϑ_6	-0.356	0.179	-0.356

Table 22-9. Estimated management quantities (95% confidence intervals) for the model calibration. The estimates were replicated to describe two scenarios over future years: a) constant 2010 fishing costs and fishing power, and b) 3% year^{-1} increased costs and power. Variation in maximum economic yields (MEY_{vf}: including both variable and fixed costs) are shown for the 2010 average number of days fished per boat per year ($\bar{d}$, Table 22-2), twice ($2\bar{d}$) average number of days and variable costs only (MEY_v: fixed costs and $\bar{d}$ cancelled from profit equation π_y).

Quantities	a) Constant 2010 fishing costs and power	b) 3% year^{-1} increased costs and power
Harvest (t)		
MSY	3100 (2454 : 3612)	3100 (2454 : 3612)
$MEY_{vf}\left(\bar{d}\right)$	1253 (641 : 1854)	1453 (905 : 1949)
$MEY_{vf}\left(2\bar{d}\right)$	1909 (1497 : 2273)	1962 (1564 : 2324)
MEY_v	2521 (2176 : 2828)	2470 (2121 : 2806)
Annual fishing effort (boat-days)		
E_{MSY}	38002 (27035 : 50754)	28300 (20110 : 37663)
$E_{MEYvf}\left(\bar{d}\right)$	7470 (3577 : 11158)	6667 (3970 : 9531)
$E_{MEYvf}\left(2\bar{d}\right)$	12869 (9425 : 16467)	9972 (7501 : 12565)
E_{MEYv}	19892 (15552 : 24049)	14307 (10977 : 17676)

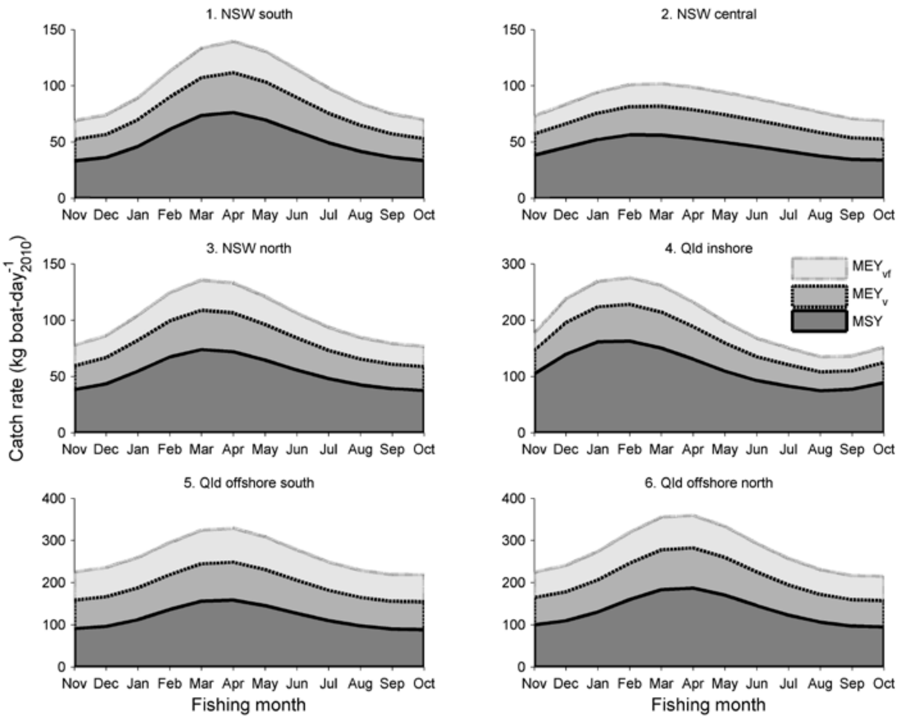


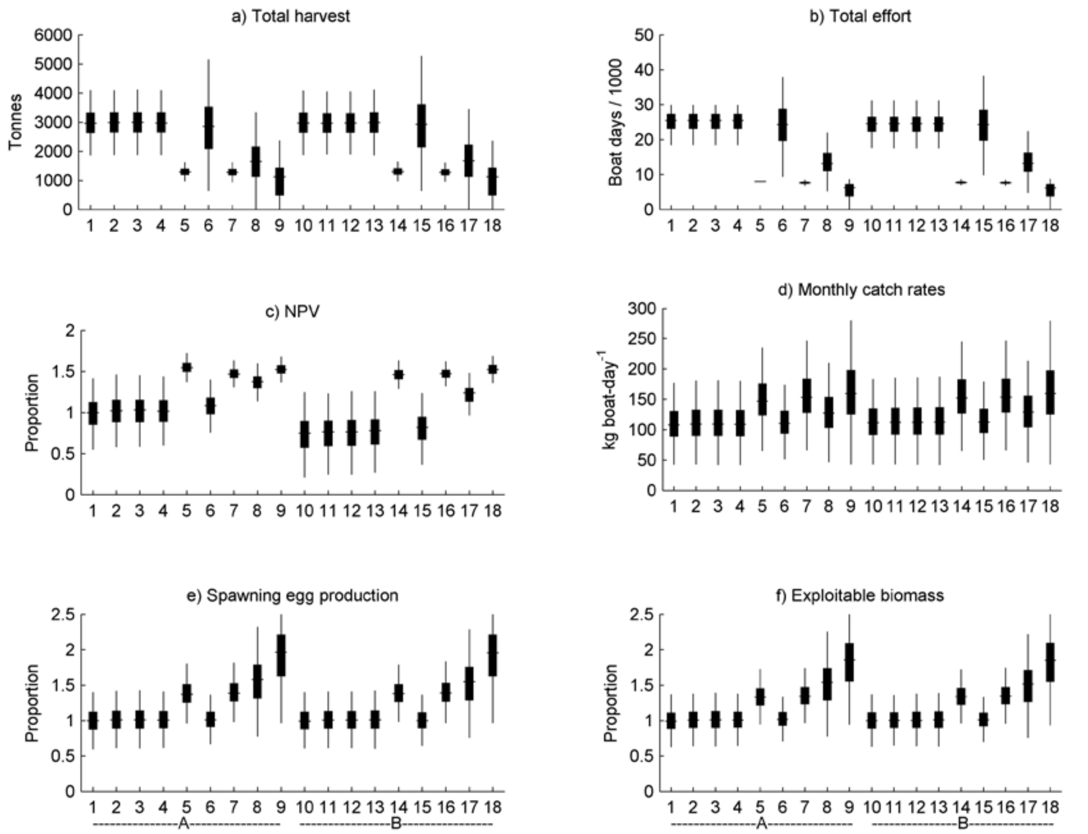
Figure 22-7. Mean monthly catch rate targets for maximum sustainable yield (MSY), maximum economic yield for variable costs (MEY_v) and $MEY_{vf}(\bar{d}$) for variable plus fixed costs by fishing region. Catch rates were standardized to 2010 fishing power.

22.3.2 Simulation of management procedures

The results of simulating management procedures were as follows (see Figure 22-8 and the probabilities of catch-rate control rules closing fishing regions, plotted in Figure 22-9):

Management procedures 1 to 4 (maximum $E_{status\text{-}quo} \approx 30000$ boat-days year^{-1})

- There were no significant changes in EKP performance measures (cases 1–4 and 10–13), except that profit under increasing fishing costs and fishing power (cases 10 to 13) declined about 20%.
- Expected annual harvests were about 3000 t, at a catch rate of 110 kg boat-day^{-1}.
- Management by regional monthly closures, with status quo fishing effort, resulted in no change in egg production or exploitable biomass.



Group A: 1. Oct 4, 2. Jan 1&4, 3. Jan 4-6, 4. Jan 1-6, 5. Jan1-6, 6. E_{MSY} $CPUE_{MSY}$, 7. E_{MEY} $CPUE_{MSY}$, 8. E_{MSY} $CPUE_{MEYv}$, 9. E_{MEY} $CPUE_{MEYv}$

Group B: 10. Oct 4, 11. Jan 1&4, 12. Jan 4-6, 13. Jan 1-6, 14. Jan1-6, 15. E_{MSY} $CPUE_{MSY}$, 16. E_{MEY} $CPUE_{MSY}$, 17. E_{MSY} $CPUE_{MEYv}$, 18. E_{MEY} $CPUE_{MEYv}$

Figure 22-8. Performance measures over ten future years for nine different EKP management procedures (Table 22-7); boxes 1–9 are for scenario A (2010 costs and fishing power) and 10–18 scenario B (3% increases in both costs and fishing power). The first row of plots a) and b) represented industry functioning, the middle plots c) and d) indicated economic conditions, and the bottom plots e) and f) measured population change. The relative measures in plots c), e) and f) were scaled against status quo strategy 1 (median =1). The plots display the simulated distributions (1000 samples) around their medians (line in the middle of each box). The bottom and top of each "box" were the 25th and 75th percentiles. The whisker length indicated approximate 95% coverage of the simulations.

Management procedure 5 (E_{MEYfv} ≈ 8000 boat-days year^{-1})

- Compared to procedures 1 to 4, there were 35–50% increases in profit, catch rates, spawning and biomass (cases 5 and 14).
- Annual harvests were more than halved at about 1300t.
- Reduced fishing effort provided larger overall profit but smaller total harvest.

Management procedure 6 (E_{MSY} ≈ 38000 boat-days year^{-1} and $CPUE_{MSY}$ control rules)

- Compared to procedures 1 to 4, there were no significant changes in performance measures (cases 6 and 15).
- Annual harvests and fishing efforts were highly variable.
- The probability of closing fishing regions after April (half way through the fishing year) was high. The region 4 closure probability was over 50% after February. Increasing fishing costs and fishing power did not significantly change the closure probabilities.
- Catch rate control rules maintained the population status by reducing the length of the fishing season.

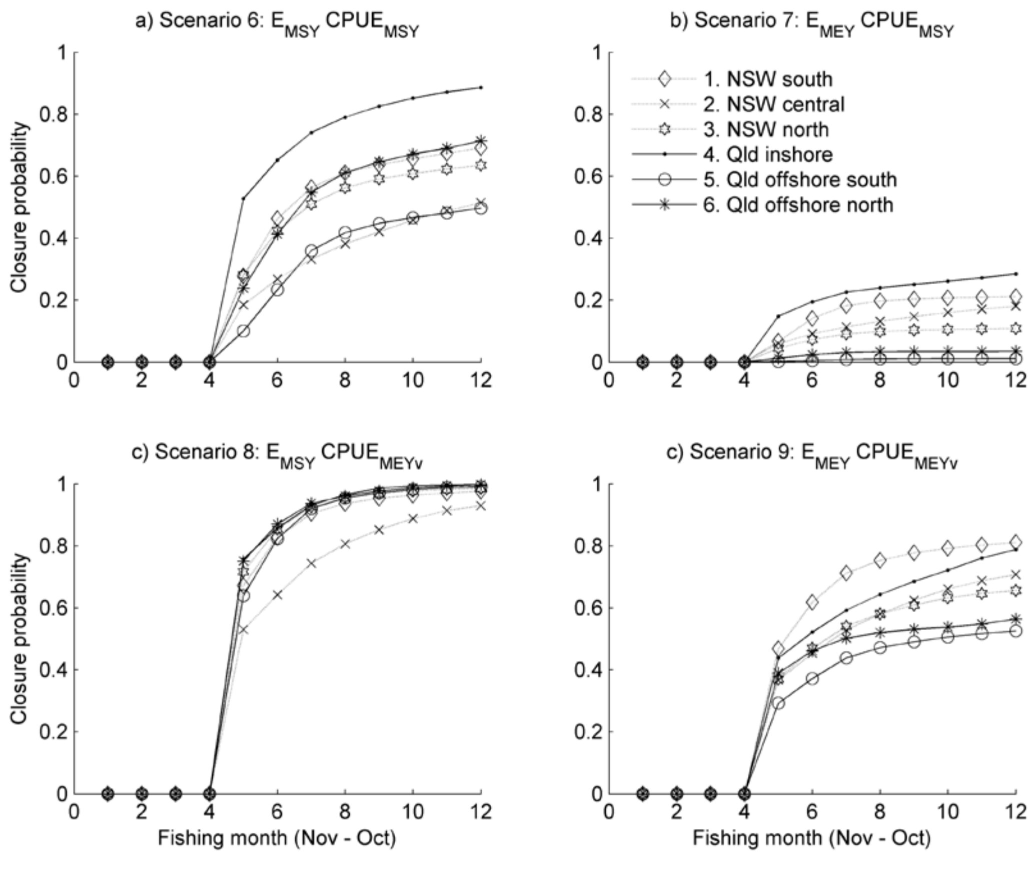


Figure 22-9. Regional closure probabilities for management performance using catch rate reference points.

Management procedure 7 (E_{MEYfv} ≈ 8000 boat-days year^{-1} and $CPUE_{MSY}$ control rules)

- Results (cases 7 and 16) were similar to management procedure 5, with 35–50% increases in profit, catch rates, spawning and biomass compared to procedures 1 to 4.
- Annual harvests were more than halved at about 1300t from 8000 boat-days.
- The probabilities of regional closures were substantially less compared to procedure 6 using E_{MSY}. Regions 1 and 4 had nearly a 20% chance of closure after June. The probabilities were less than 5% for regions 5 and 6.
- Reduced fishing effort together with catch-rate control rules maintained higher and more profitable EKP population than status quo. Spawning and biomass levels were not significantly higher compared to procedure 5.

Management procedure 8 (E_{MSY} ≈ 38000 boat-days year^{-1} and $CPUE_{MEYv}$ control rules)

- Compared to procedures 1–4 and 6, there were significant reductions in total fishing harvest and effort (cases 8 and 17). Relative profit, catch rates, spawning and biomass levels were all higher.
- Annual harvests were about 1600 t, and total effort was managed at about 13000 boat days.
- The probability of closing fishing regions after February (4 months into the fishing year) was high.
- Catch rate control rules maintained a higher EKP population status by reducing the fishing year, resulting in a typical closure from March to October.

Management procedure 9 (E_{MEYfv} ≈ 8000 boat-days year^{-1} and $CPUE_{MEYv}$ control rules)

- This management resulted in the highest catch rates, spawning and biomass (cases 9 and 18).
- Compared to procedures 1 to 4, relative profit was about 50% higher.
- Annual harvests were the lowest of all management procedures, at about 1100t, with about 6000 boat-days effort.
- The closure probabilities were higher compared to procedure 7 with the same fishing effort.
- Despite the lower fishing effort, the catch-rate control rule still reduced the fishing season, with a typical closure from March to October.

22.4 Discussion

The results provide a major advance over the previous assessment (Ives and Scandol 2007; O'Neill *et al.* 2005), in that EKP has been assessed as a whole stock transcending jurisdictional borders and operational economics have become a research focus. The results outlined management paths to keep EKP fishing sustainably and more profitable.

Our stock steepness estimate of 0.36 (Table 22-8) was in line with other Penaeid prawn analyses reported by Ye (2000). This is an important parameter describing the relationship between annual spawning (egg production) and the following year’s recruitment (number of new prawns entering the ocean fishery). In Australia, estimates of steepness in the Northern Prawn Fishery have ranged from 0.26 to 0.36 for the two species of tiger prawns (Dichmont *et al.* 2001), and the estimate for tiger prawns in the Torres Strait was 0.46 (O'Neill and Turnbull 2006). Previous analyses of EKP steepness compared values of 0.56, 0.4 and 0.37 and showed management implications of low steepness (O'Neill *et al.* 2005). The longer assessment time-series, compared to O'Neill *et al.* (2005) and Ives and Scandol (2007), allowed more accurate estimates of EKP productivity.

22.4.1 Management procedures

In the simulations, management procedure 7, which used E_{MEY} and $CPUE_{MSY}$, performed the best in the sense of increased fleet profit and catch rates, and low probability of regional closures. This was followed closely by management procedure 5 which used E_{MEY} with a January fishing closure. For these procedures, combined fleet profit, catch rates, spawning egg production and biomass were all significantly higher than status quo. They were also robust to future increases in fishing costs and fishing power. Management procedure 9 resulted in similar increased profit and catch rate, but less predictability with potentially short fishing seasons.

A major finding is that it is important to limit fishing effort to a level less than E_{MSY}: catch rate control rules were effective under E_{MEY} but much less so under E_{MSY}, where they successfully reduced effort but caused uncertain harvest and often closed fishing regions mid-year.

The setting of the catch-rate trigger required knowledge of where and when EKP were abundant and information on profitable catch rates (Figure 22-7). In general, EKP recruitment and movement dynamics were known (Braccini *et al.* 2012b). However, year-to-year variation in timing of recruitment and movement dynamics may occasionally reduce catch rates. No cost-effective monitoring was available to guard against such circumstances which produce misleading abundance signals. We note that Walters and Martell (2004) caution that in-season management procedures should be used with care in managing total harvests and efforts.

Notwithstanding the above limitations, $CPUE_{MSY}$, in combination with an effort limit of E_{MEY}, was found to be an appropriate trigger point given significant catch rate observation error. This trigger point minimized management mistakes due to data errors. Even so, these controls alone may not always be a safeguard against unpredictable situations or issues. Regional changes in fishing effort should be monitored carefully given that hyperstability bias can be caused by temporal changes in fishing power (catchability) and where and how vessels fish.

Analysis showed that single-month fishing closures were not effective at improving industry harvests, economics or population status. However, specific spatial or seasonal closures could still be considered in order to provide vessel repair time for the fleet and to reduce the harvest of small prawns.

An additional ability of the stock operating model was to estimate management procedures for optimal allocation of regional and seasonal levels of fishing, assuming a single jurisdiction. At the time of this research, such predictions were not desired. Fishery managers and stakeholders tabled specific procedures to evaluate (Table 22-7), with no major alterations to traditional fishing patterns; particularly early-season fishing for Christmas markets. In addition, stakeholder objectives included free movement of vessels, high catch rates, valuable licence units, and equitable access (Dichmont *et al.* 2013).

Even though optimal-allocation procedures were not of current interest for EKP, their governance design could be of future benefit across fisheries; for hypothetical examples see Dichmont *et al.* (2013). Modelling of innovative patterns of regional and seasonal fishing across fisheries may identify new ways to increase profit for the fleet as a whole, avoid excess harvest of small prawns, and improve efficiencies of management and monitoring. Evaluation would require further model dynamics to allow for vessels fishing other otter-trawl sectors in Queensland, including Moreton Bay, saucer scallop, red-spot king prawn and tiger prawn; and catching other valued species in New South Wales, such as cephalopod, school whiting and school prawn.

22.4.2 Reference points

Simulation identified that spawning egg production (S) and exploitable biomass (B) ratios were above reference limits of 50% virgin S_{1958} and 40% virgin B_{1958}. MSY was estimated at about 3100t. Fishing effort estimates for E_{MSY} ranged from 38,000 down to 28,000 boat days, dependent on the trend in fishing power. Considering decadal management and a potential strong upward trend in fishing power, it would be safer to take E_{MSY} as about 28000 boat-days per year. These values were similar to those estimated by O'Neill *et al.* (2005). The uncertainty surrounding the value of E_{MSY} was typical for a fisheries assessment, and confirmed that target fishing efforts should not approach this limit due to risks of over fishing and less profitable catch rates (Garcia and Staples 2000).

Estimates of MEY for EKP were strongly influenced by the reported high costs (variable and fixed) of fishing, the assumed average number of days fished per vessel year ($\overline{d}$) and fishing power. The ratio of MEY to MSY was especially influenced by the high annual fixed costs (Table 17-10). The MEY ranged between 1300t and 2000t and E_{MEY} between 7000 and 13,000 boat-days. A higher value of $\overline{d}$ significantly increased profit, but reduced the number of vessels, which may negatively impact social objectives of the fishery (Pascoe *et al.* 2013; Wang and Wang 2012). Operationalizing MEY in a fishery requires an agreed set of rules, assumptions and strong industry commitment (Dichmont *et al.* 2010). For MEY_v (estimate for MEY under variable costs only), estimated tonnages were higher at about 2500t and E_{MEYv} between 14,000 and 20,000 boat days per year.

22.5 ACKNOWLEDGEMENTS

The research was supported and funded by the Australian Government's Fisheries Research and Development Corporation (FRDC), New South Wales Department of Primary Industries and Queensland Department of Agriculture, Fisheries and Forestry. Special thanks also go to Tony Courtney, Marco Kienzle, Steve Montgomery and Sean Pascoe for their assistance with modelling data and analyses. The Queensland long-term monitoring programme supplied data from their annual EKP recruitment survey. We gratefully acknowledge the fishery managers, stakeholders and FRDC project 2008/019 steering committee who contributed to the design of the management procedures.

23 Appendix 11. Latitudinal and seasonal effects on growth of the Australian eastern king prawn (*Melicertus plebejus*)

Luke R. Lloyd-Jones, You-Gan Wang, Anthony J. Courtney, Andrew J. Prosser, and Steven S. Montgomery

Abstract: The growth of the Australian eastern king prawn (*Melicertus plebejus*) is understood in greater detail by quantifying the latitudinal effect. The latitudinal effect is the change in the species' growth rate during migration. Mark–recapture data (N = 1635, latitude 22.21°S–34.00°S) presents northerly movement of the eastern king prawn, with New South Wales prawns showing substantial average movement of 140 km (standard deviation: 176 km) north. A generalized von Bertalanffy growth model framework is used to incorporate the latitudinal effect together with the canonical seasonal effect. Applying this method to eastern king prawn mark–recapture data guarantees consistent estimates for the latitudinal and seasonal effects. For *M. plebejus*, it was found that growth rate peaks on 25 and 29 January for males and females, respectively; is at a minimum on 27 and 31 July, respectively; and that the shape parameter, k (per year), changes by –0.0236 and –0.0556 every 1 degree of latitude south increase for males and females, respectively.

Résumé : La quantification de l'effet latitudinal permet une compréhension plus détaillée de la croissance de la crevette royale orientale australienne (*Melicertus plebejus*). L'effet latitudinal est la variation du taux de croissance de l'espèce durant la migration. Des données de marquage-recapture (N = 1635, latitude 22,21°S–34,00°S) décrivent le déplacement vers le nord de crevettes royales orientales, les crevettes de Nouvelle-Galles-du-Sud présentant un important déplacement moyen de 140 km (écart-type : 176 km) vers le nord. Un cadre reposant sur le modèle de croissance de von Bertalanffy est utilisé pour incorporer l'effet latitudinal à l'effet saisonnier canonique. L'application de cette méthode aux données de marquage-recapture pour la crevette royale orientale garantit l'estimation cohérente des effets latitudinal et saisonnier. Pour *M. plebejus*, il a été observé que le taux de croissance atteint un maximum les 25 et 29 janvier et un minimum les 27 et 31 juillet, respectivement, pour les mâles et les femelles, et que les changements du paramètre de forme, k (par année), sont de –0,0236 et –0,0556 pour chaque augmentation d'un degré de la latitude sud, respectivement, pour les mâles et les femelles.

[Traduit par la Rédaction]

Introduction

The growth of fish and other aquatic fauna can be affected by many factors: environmental (food availability, temperature), anthropogenic (fishing, habitat degradation), and biological (biochemical). Assessing these influences can provide a more detailed understanding of the growth of a particular species.

The growth of organisms in subtropical and temperate waters does not necessarily proceed at the same rate throughout the year (Haddon 2011). If seasonal growth dependence is likely, it may be necessary to incorporate this into the growth analysis (Pitcher and MacDonald 1973; Shepherd and Hearn 1983). Location of a population may also change substantially during the seasons, especially for migratory species. Therefore, a coupled growth model that incorporates the locational and seasonal changes makes sense.

Species distributed over large geographical areas exhibit body size gradients, with the majority of larger adults being recorded in colder environments (Ashton 2004; Partridge and French 1996). The geographic variation in body size is consistent with the intraspecific version of Bergmann's rule, which states that races of a species, especially endotherms, tend to be larger in colder environments to limit heat loss

Received 20 December 2011. Accepted 30 June 2012. Published at www.nrcresearchpress.com/cjfas on xx August 2012.
J2011-0518
Paper handled by Associate Editor Yong Chen.

L.R. Lloyd-Jones and Y.-G. Wang.* Centre for Applications in Natural Resource Mathematics (CARM), School of Mathematics and Physics, The University of Queensland, St. Lucia, Qld 4067, Australia.
A.J. Courtney and A.J. Prosser. Queensland Department of Agriculture, Fisheries and Forestry, Ecosciences Precinct, Joe Baker Street, Dutton Park, Queensland, 4102, Australia.
S.S. Montgomery. Cronulla Fisheries Centre, 202 Nicholson Parade, Cronulla, NSW, 2230, Australia.

Corresponding author: You-Gan Wang (e-mail: you-gan.wang@uq.edu.au).

* Present address: Priestley Building 67, St. Lucia, Department of Mathematics, The University of Queensland, Brisbane, Qld, 4072, Australia.

Can. J. Fish. Aquat. Sci. 69: 1–14 (2012) doi:10.1139/F2012-072 Published by NRC Research Press

Table 1. Summary of eastern king prawn tag and release studies in Queensland and New South Wales.

Area	Release date	No. released	No. recaptured	Percent recaptured
Fraser Island (25.7°S)	Nov. 1990	4749	984	20.7
Moreton Bay (27.3°S)	Nov. 1990	1607	109	6.8
East Moreton Island (27.3°S)	Nov. 1990, Feb. 1991	2676	206	7.7
South West Rocks (30.8°S)	Nov. 1991	2944	186	6.3
	Jan. 1992	2812	402	14
	Dec. 1991	3096	161	5.2
Newcastle (33.2°S)	Mar. 1992	3067	100	3.3
	Feb. 1991	1221	277	22.7
Botany Bay (34.0°S)	Oct. 1991	1058	556	52.6
	Feb. 1992	710	404	56.9

due to a smaller surface area to body mass ratio (Angilletta et al. 2004; Atkinson and Sibly 1997). However, it is controversial to apply this rule to ectotherms because their body temperature fluctuates rapidly with ambient temperature (Geist 1987). The thermal plasticity of body size, dubbed the temperature size rule, has been observed in bacteria, protists, plants, and animals, making it one of the most taxonomically widespread rules in biology (Angilletta et al. 2004).

One ectothermic species that is likely to experience a latitudinal change in growth is the Austalian eastern king prawn (*Melicertus plebejus*, previously known *as Penaeus plebejus*). *Melicertus plebejus* inhabits coastal waters of eastern Australia and has been recorded as far north as Hayman Island (20°S), as far south as Tasmania (42°S), and at depths up to 350 m (Courtney et al. 2007). This species is the most commercially valuable prawn species in eastern Australia, with current landings (total east coast) valued at more than $30 million (O'Neill et al. 2005; Glaister et al. 1987).

Ruello (1975) commented that *M. plebejus* migrate out of the New South Wales estuaries in the surface waters of the night ebb tides. During the darker half of the lunar cycle, they move into deeper water while moving along the coast in a north to northeast direction. Interestingly, *M. plebejus* move longer distances than most other penaeids (Ruello 1975; Somers and Kirkwood 1984; Sheridan et al. 1987). Via a tagging study, Montgomery (1990) showed that all tagged *M. plebejus* that were recaptured away from their point of release had moved north. Additionally, in a mark–recapture study of *M. plebejus*, Glaister et al. (1987) showed that prawns that moved longer distances did so in a northerly direction. Northerly movement is coupled with a movement into deeper waters as prawns from New South Wales reach the Queensland coast. According to Glaister et al. (1987), the east coast fishery of *M. plebejus* can be considered to consist of two substocks: those prawns north of 27.25°S that derive their recruitment from Moreton Bay and those prawns from 34°S to 27.25°S that recruit from Clarence River (29.43°S) south. Ruello (1975) remarked that the distribution of eastern king prawns is most likely influenced by the East Australian Current, an oceanic current system off the east coast of Australia. Knowledge of the growth of the population as they migrate is potentially important when evaluating management strategies, for example, temporal and spatial closures (Rijnsdorp and Pastoors 1995; Helser and Lai 2004). Investigating body size gradients and quantifying the change in growth at different latitudes is potentially of great interest.

Mark–recapture studies are frequently conducted to quantify growth as well as rates of movement–migration and abundance (Quinn and Deriso 1999). The von Bertalanffy growth model is often applied to mark–recapture data and is considered to model growth well (Chen et al. 1992). Determining adequate parameter estimates of the von Bertalanffy model such that growth is modelled accurately is a complex problem. This is especially evident when individual variability is considered (e.g., Wang and Thomas (1995); Wang and Die (1996); Wang and Somers (1996)). James (1991) provided a method for estimating the von Bertalanffy growth parameters via unbiased estimating equations. Wang (1999) developed a generalized von Bertalanffy growth model framework to incorporate stochastic components and explanatory variables for growth that vary with time. Xiao (1999) provided a more general framework to incorporate time-dependent factors (i.e., ambient temperature, food availability, and latitude) into growth models.

This paper derives estimating functions, based on the work of Wang (1999), that incorporate latitudinal and seasonal effects. It is hypothesized that these two factors influence the growth rate of species that migrate latitudinally over large distances. This idea is tested using eastern king prawn mark–recapture data.

Materials and methods

Data

To illustrate the method, eastern king prawn mark–recapture data were analysed. These data were obtained from mark–recapture studies undertaken in New South Wales and Queensland. Approximately 3000 recaptures were taken between 23.78°S and 34°S (Table 1). For the New South Wales data, mark–recapture experiments were done in Botany Bay (34°S) and offshore from Newcastle (30°S) and South West Rocks (32°S) in New South Wales, Australia (Table 1). Experiments offshore were done within 2.8 km of the coast off each location; each of these study areas were closed to commercial fishing for 1 month after each tagging experiment to allow tagged prawns time to disperse. For the same reason, Botany Bay was closed to fishing for 48 h after each release. Trawls of 10 min in Botany Bay and of 20 min for offshore locations were done aboard chartered commercial trawlers or the NSW Fisheries' FRV Kapala to collect eastern king prawns for tagging. Live prawns longer than 20 mm carapace length (CL) were sorted from the catch and placed in 450 L tanks filled with salt water. Prawns were tagged with individually numbered yellow streamer tags and measured to the nearest whole millimetre with dial callipers between the base of the eye orbit and the posterior margin of the carapace. Tagged prawns were placed in release canisters (Emiliani 1971) submerged in 450 L tanks of salt water to await release. Prawns were inspected just prior to release, and any damaged individuals were discarded. They were released in canisters back onto the bottom in the vicinity from where they had been caught.

In 1990 and 1991, tag–release studies were undertaken in Queensland to quantify population parameters for management of the fishery. Chartered commercial trawlers and government research trawlers were used as platforms to capture, tag, and release the prawns. The duration of the trawls used to catch the prawns was relatively short to reduce stress and injury to the prawns prior to tagging (i.e., less than 20 min, equivalent to the New South Wales methods). After each trawl, live prawns larger than 20 mm CL were sorted from the catch and immediately placed in a 400 L tank with flow-through sea water. Apparently healthy individuals were identified in the tank and chosen for tagging. Just before tagging, the size and sex of the prawn were determined and recorded. An individually numbered streamer tag was inserted through the abdomen of each tagged prawn using an attached needle, between the dorsal gut and the ventral nerve chord. After the tag was inserted, the needle was torn off the tag. Tagged prawns were then placed inside an aluminium release cage, which was submerged in a second larger tank. When sufficient numbers of prawns were tagged (i.e., ≈200), the release cage was closed, removed from the tank, and lowered to the bottom using a rope. Once the cage came into contact with the bottom, a mechanical release system was activated to open the cage, allowing the tagged prawns to escape and disperse. The cage was then retrieved. As an incentive to fishers, small financial rewards were provided for each recaptured prawn. All recaptures were caught by commercial otter trawl fishers, who in addition to providing the recaptured tagged prawn, also provided information on its location and date of recapture, using prawn recapture kits that were provided to them in the days prior to release.

Following Somers and Kirkwood (1984), recaptured prawns that were at liberty less than 14 days were omitted from the analyses, leaving a total of 1559 observations. Of these 1559, 678 were male and 881 were female. This practice is carried out to ensure that the data analysed contain the best information possible. Growth before this is considered to be unrecognizable when compared with the error incurred from measurement. Theoretically, these data with very short time at liberty would provide measurement error information. However, if the growth is retarded (temporally) and recovered after 2 weeks, these data can lead to a very biased estimation (Pilling et al. 2002; Wang 1998; Hampton 1986). The raw data contains many recaptures (>500) with less than 14 days at liberty. Retaining these data may provide excess noise, making model estimation more difficult and providing biased estimates. The removed samples also contribute to latitudinal noise, making it more difficult to distinguish between small drifts and actual migration. It is noted that these removed data may contain information on measurement error, which is a trade-off from this practice.

Table 2. Summary of data for male and female eastern king prawns.

	L_1 (mm)	L_2 (mm)	$L_2 - L_1$ (mm)	T (days)
Males				
Mean	27.8	32.0	4.27	48.7
SD	3.46	4.39	3.67	47.0
Range	18.6, 39.2	20.7, 51.6	–5.4, 21.1	15, 623
Females				
Mean	29.5	35.4	5.92	48.4
SD	4.83	6.58	5.12	51.7
Range	17.5, 42.1	19.9, 57.4	–3.8, 30.8	15, 942

Before implementing the model, exploratory data analysis was carried out. Sexes were analysed separately, since von Bertalanffy growth parameters vary substantially between male and female *M. plebejus*, particularly asymptotic length (Glaister et al. 1987). If L_1 and L_2 denote the observed lengths (mm carapace) at release and recapture, respectively, and T denotes the time at liberty (days), then the data can be summarized as in Table 2. The data presents good variability with major times at liberty and large ranges of growth for many size classes (Table 2). The distribution of mark and recapture numbers is centred around the summer months, with maximum releases in November and maximum recaptures in December (Table 3). The tagging and releasing of prawns was undertaken from November to March (Table 3), as it is generally when small, recruiting eastern king prawn are present in shallow coastal waters of eastern Australia. It is noted that the recaptures are a reflection of fishing effort, with the predominance of large numbers of recaptures in peak fishing months.

The data present a substantial northerly movement by the New South Wales prawns and a significant, but reduced, northerly migration by the Queensland prawns (Table 4; Figs. 1 and 2). To standardize the movement of all animals, a linear interpolation was carried out and plotted. This was done because it is deceptive to evaluate the movement, since all plotted points have differing times at liberty (see Figs. 1d and 2d). These figures reinforce the major northerly migration undertaken by this species. All top movers (>5° movement) began migration from 34°S, with a maximum individual northerly movement of 802 km (7.22°) for males and 720 km (6.48°) for females. Given migration is present in the data, an analysis of how this change in location affects the growth of the eastern king prawn is both interesting and justified.

Growth model

The von Bertalanffy model is considered to simulate growth of aquatic species very well (Chen et al. 1992). Wang (1999) outlined a general method for incorporating covariates that contribute to the growth rate of a species into the von Bertalanffy model. Following the work of Wang (1999), we proceed to derive the coupled latitudinal and seasonal von Bertalanffy model.

The following generalized von Bertalanffy model was proposed by Wang (1999):

$$(1) \qquad L'(t) = [L_\infty - L(t)]g(\boldsymbol{\theta}, \boldsymbol{x}_t) + \sigma(t)\varepsilon(t)$$

Table 3. Distribution by number of tag–release and recapture times over 1 year for male and female eastern king prawns.

Sex and capture	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Males												
Mark	34	76	5	0	0	0	0	0	0	44	506	13
Recapture	80	45	113	19	24	9	5	0	0	1	35	348
Females												
Mark	40	106	10	0	0	0	0	0	0	81	622	22
Recapture	92	59	153	28	27	5	7	1	3	0	53	453

Table 4. Summary (number, average (km), and sample standard deviation (km)) of movement between gender and data origin for eastern king prawns.

	All			Queensland						NSW					
				Male			Female			Male			Female		
Direction	No.	Avg.	SD	No.	Avg.	SD	No.	Avg.	SD	No.	Avg.	SD	No.	Avg.	SD
North	830	37	91	318	15	9	371	15	37	58	107	148	73	144	170
South	382	6	11	107	7	14	120	7	12	62	3	2	93	2	1
No move	359	—	—	94	—	—	51	—	—	82	—	—	130	—	—
West	491	2	8	187	2	9	262	2	9	18	3	7	24	2	1
East	931	16	34	288	7	9	317	7	9	133	26	48	182	31	51
No move	149	—	—	1	—	—	6	—	—	51	—	—	90	—	—

with $\mathcal{E}(t)$ being a zero mean error term representing the environmental perturbation and $\sigma(t)$ accounting for the heteroscedasticty of the error process. The latitudinal and seasonal effects are incorporated into the model via a link function denoted $g(\theta, Xt)$, where θ can be a vector or a scalar. The solution to the differential eq. 1 with initial conditions) $L(b_0) = l_o$ has the form

$$(2) \quad L(t) = l_0 + [L_\infty - l_0]\{1 - \exp[-z(b_0, t)]\} + w(b_0, t)$$

In eq. 2:

$$(3) \quad z(b_0, t) = \int_{b_0}^{t} g(\boldsymbol{\theta}, \boldsymbol{x}_u)\, \mathrm{d}u \text{ and}$$

$$(4) \quad w(b_0, t) = \int_{b_0}^{t} \{\exp[\int_{t}^{u} g(\boldsymbol{\theta}, \boldsymbol{x}_s)\, \mathrm{d}s]\sigma(u)\varepsilon(u)\}\, \mathrm{d}u$$

To incorporate the latitudinal effect into our model we let

$$(5) \quad g(\theta, t) = k + \theta[d(t) - \bar{d}]$$

be the link function. In eq. 5, k represents the growth rate at latitude $d(t) = \bar{d}$, where $\bar{d}$ is suitably chosen such that it represents the data. A linear model was selected because it adequately describes the relationship between growth and latitude over the mark–recapture study area. Using a mark–recapture framework, the function $d(t)$ describes the linear interpolation between the latitude at mark d_1 and latitude at recapture d_2 after time t. Let

$$(6) \quad d(t) = d_1 + \frac{d_2 - d_1}{t_2 - t_1}(t - t_1)$$

with t_1 and t_2 being the time at mark and the time at recapture, respectively, relative to 1 January of no particular year.

It can also be hypothesized that at different latitudes seasonality affects growth differently. To account for the seasonality, we express the final link function as a linear combination of seasonal and latitudinal effects

$$(7) \quad g(\boldsymbol{\theta}, t) = k + \theta_1\left[d_1 + \frac{d_2 - d_1}{t_2 - t_1}(t - t_1) - \bar{d}\right] + \theta_2\cos(2\pi t) + \theta_3\sin(2\pi t)$$

where the seasonal component of eq. 7 (eqs. 3 and 4) represent the canonical fisheries seasonal growth model (Pitcher and MacDonald 1973; Pauly and Gaschutz 1979). If a similar longitudinal expression was of interest, the following link function may describe a longitudinal effect:

$$(8) \quad g(\theta, t) = k + \theta_1 d_y(t) + \theta_2 d_x(t) + \theta_3\cos(2\pi t) + \theta_4\sin(2\pi t)$$

where

$$(9) \quad d_x(t) = d_{x1} + \frac{d_{x2} - d_{x1}}{t_2 - t_1}(t - t_1)$$

In eqs. 8 and 9, d_x represents the longitudinal function and d_y the latitudinal function. Please note that this link function is for use with species that have a suspected linear change in growth with respect to longitude. A longitudinal effect has not been included in this analysis; reasons for doing so are included in the Discussion.

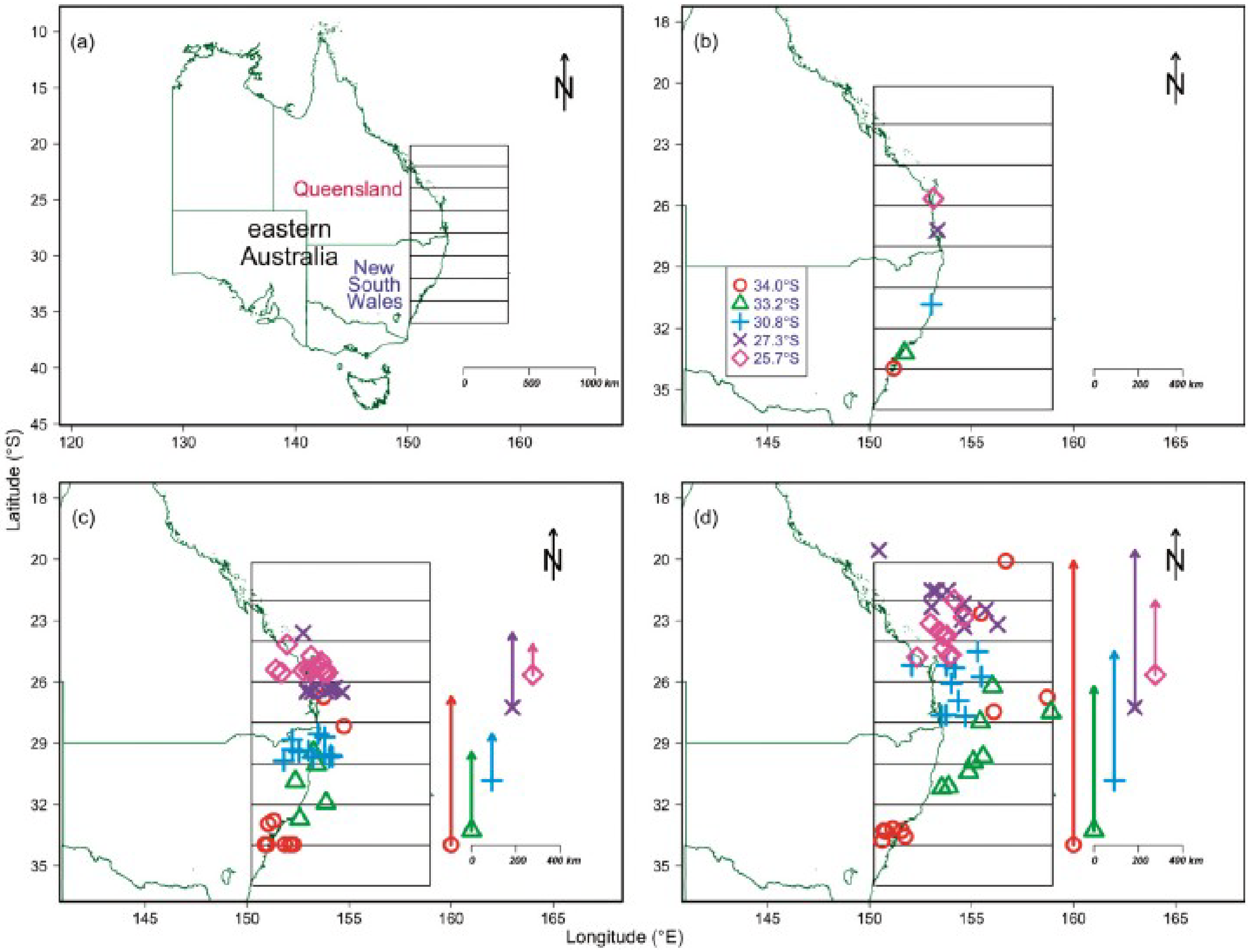
Estimation of von Bertalanffy model parameters from mark–recapture data

Having described the general von Bertalanffy growth model, it is necessary to determine an expression such that a mark–recapture study may be used. Following Wang (1999), we assume the existence of measurement error () with each measurement of size

$$L_j = l_j + w_j + \gamma_j$$

where l_j is the expected size of the ith ($i \in (1, \ldots, n)$) recaptured animal at time t_j ($j = 1, 2$) conditional on the asymptote being L_∞. The term w_j represents process error, and for con-

Fig. 1. Male eastern king prawn mark–recapture data from the east coast of Australia: (a) position reference panel, (b) tag and release locations, (c) best recapture points based on largest movement (>1°) with a longitudinal displacement for clarity, (d) theoretical movement (latitudinal linear interpolation) after 1 year, with a longitudinal displacement for clarity (only top 10 movers represented for clarity). Vertical lines represent the range of movement for each symbol and color type.



venience $w_j + \gamma_j$ is denoted as e_j. Process error for L_1 has no effect on the observed growth increment, whereas measurement error would have an effect. On the other hand, both process and measurement error have an effect on L_2. Therefore, e_1 represents measurement error, while e_2 combines both process and measurement errors. The growth increment stated by Wang (1999) is

$$(10) \qquad L_2 - L_1 = (L_\infty - L_1)\{1 - \exp[-z(t_1, t_2)]\} + \xi$$

where

$$(11) \qquad \xi = e_2 - e_1 \exp[-z(t_1, t_2)] + (L_\infty - l_\infty)\{1 - \exp[-z(t_1, t_2)]\}$$

Equation 11 represents a random variable with mean zero (normality is not required). Note that in this paper we allow L_∞ to vary between individuals with mean l_∞. This is done to ensure that we take into account the variability of L_∞ between individuals. The method of James (1991), which this model is based on, guarantees that if L_∞ has variability then the estimates provided are consistent. This is a key point of difference with the method of Fabens (1965), which provides biased estimates if L_∞ is variable. Given the model is based on that of James (1991), L_∞ is allowed to vary without risk of biased estimates.

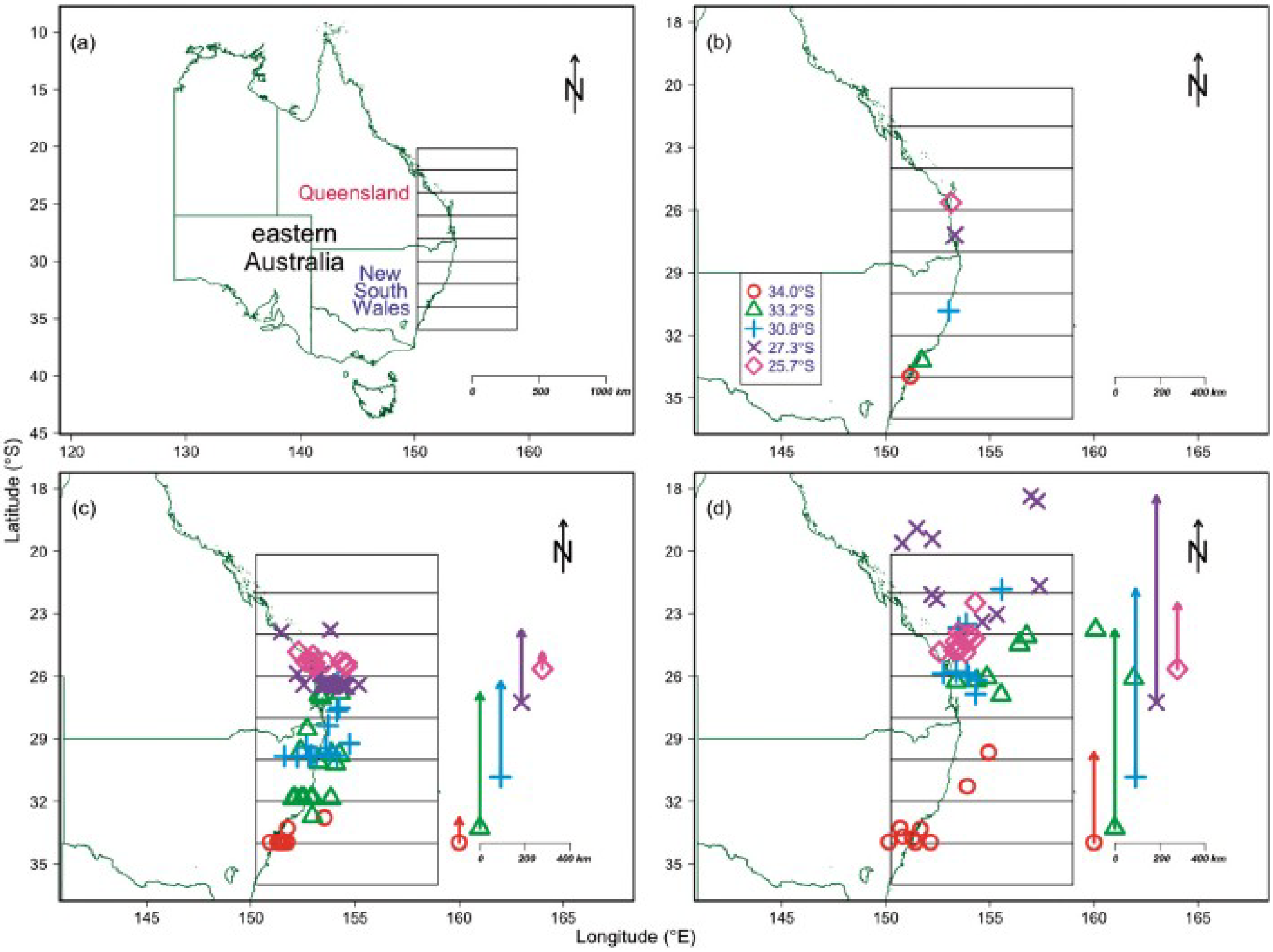
To determine the parameter estimates, the following estimating functions are used:

$$(12) \qquad f_0 = \sum_i \eta_i$$

$$f_j = \sum_i \frac{\partial z(t_{1i}, t_{2i})}{\partial \theta_j} \eta_i$$

where

Fig. 2. Female eastern king prawn mark–recapture data from the east coast of Australia: (a) position reference panel, (b) tag and release locations, (c) best recapture points based on largest movement (>1°) with a longitudinal displacement for clarity, (d) theoretical movement (latitudinal linear interpolation) after 1 year, with a longitudinal displacement for clarity (only top 10 movers represented for clarity). Vertical



$$\eta_i = (L_{2i} - L_{1i}) - (l_\infty - L_{1i})\{1 - \exp[-z(t_{1i}, t_{2i})]\} \quad (13)$$

In eq. 12, θ_j represents the parameters of $g(\theta, x_t)$, which includes k. These estimating functions have zero expectation and therefore produce consistent estimates. They do not require distributional assumptions and allow for extra variation attributed to growth variability, stochastic fluctuations, and unexplained sources. Estimation of the vector θ requires the minimization of the sum of the estimating functions squared. Minimization of the objective function can be done via any nonlinear optimization technique.

Once parameter estimates are found, it is important to evaluate the significance of the estimate, especially when investigating the use of a new parameter. An estimate of the asymptotic covariance matrix can be found by solving

$$\mathbf{F}^{-1}\mathbf{X}\mathbf{X}'(\mathbf{F}')^{-1}$$

where $\mathbf{F}$ is the Jacobian matrix evaluated at the estimated values, and $\mathbf{X}$ is the residual matrix (see Appendix A). Once the covariance matrix is determined, standard errors and correlations can be calculated and significance testing carried out on the parameter estimates.

Estimating latitudinal and seasonal parameters for the eastern king prawn (*M. plebejus*)

Estimation of latitudinal and seasonal parameters for the eastern king prawn requires an adaption of the general model. The growth link function $g(\theta, t)$ is given by eq. 7, which via integration (Appendix B) from t_1 to t_2 leads to

$$z(t_1, t_2) = kT + \theta_1 T\left(\frac{\delta d}{2} - \bar{d}\right) + \frac{\theta_2}{2\pi}[\sin(2\pi t_2) - \sin(2\pi t_1)] - \frac{\theta_3}{2\pi}[\cos(2\pi t_2) - \cos(2\pi t_1)] \quad (14)$$

where $T = t_2 - t_1$, and $\delta d = d_2 + d_1$. The estimating functions for the parameter set $\theta = (l_\infty, k, \theta_1, \theta_2, \theta_3)$ are

Table 5. Parameter estimates (calculated at = 25°S latitude) and standard errors for male and female eastern king prawns from combined seasonal and latitudinal von Bertalanffy growth model.

	k (year^{-1})	l_∞ (mm)	θ_1 (k per 10°)	θ_2	θ_3
Males	1.43	46.7	–0.236	1.11	0.499
Estimate	0.340	2.43	0.283	0.360	0.278
SE asymptote	4.21	19.3	–0.832	3.09	1.80
z	0.0001	0	0.200	0.001	0.036
p value					
Females					
Estimate	1.46	61.1	–0.556	0.679	0.362
SE asymptote	0.368	5.36	0.346	0.235	0.210
z	3.97	11.4	–1.61	2.89	1.72
p value	0.0001	0	0.054	0.002	0.043

Table 6. Parameter correlation values.

Sex	Q_{k,l_∞}	Q_{k,θ_1}	Q_{k,θ_2}	Q_{k,θ_3}	Q_{l_∞,θ_1}	Q_{l_∞,θ_2}	Q_{l_∞,θ_3}	$Q_{,\theta_1,\theta_2}$	$Q_{,\theta_1,\theta_3}$	$Q_{,\theta_2,\theta_3}$
Male	–0.74	–0.71	–0.046	0.17	0.66	–0.61	–0.67	–0.29	–0.43	0.87
Female	–0.93	–0.87	0.46	0.74	0.85	–0.71	–0.86	–0.65	–0.80	0.83

$$
\begin{aligned}
f_0 &= \sum_i \eta_i \\
f_1 &= \sum_i T_i \eta_i \\
f_2 &= \sum_i T_i \left(\frac{\delta d_i}{2} - \bar{d}\right) \eta_i \qquad (15) \\
f_3 &= \sum_i [\sin(2\pi t_{i2}) - \sin(2\pi t_{i1})]\eta_i \\
f_4 &= \sum_i [\cos(2\pi t_{i2}) - \cos(2\pi t_{i1})]\eta_i
\end{aligned}
$$

Using these estimating functions (eq. 15), the parameters were obtained for male and female *M. plebejus* via minimizing the objective function, $F = f_0^2 + f_1^2 + f_2^2 + f_3^2 + f_4^2$, using the R programming language (http://www.r-project.org/). ***F*** must minimize to approximately 0 to meet the requirements of this method.

Results

Using generalized estimating equations to solve for parameter estimates from mark–recapture data provided interesting insights into the growth of the eastern king prawn. Assessing the results acquired from eq. 15, we can conclude that all parameter estimates are significant for a one-sided z test, except the male latitudinal effect. It is also noted that the female effect is weakly significant (Table 5). The condition that the residuals have expectation 0 must be met to reliably conclude that the method has worked. For both male and female data, the objective function converged in the order of 10^{-8}, which is sufficiently close to zero in our experience with James' (1991) method. The one-sided test is adequate as all estimates must be greater or less than 0 to make intuitive sense.

Correlations between all parameters are reported for both males and females (Table 6).

To make the seasonal growth parameters easier to interpret, they were converted to the canonical form (Pitcher and MacDonald 1973). The seasonal model component is often expressed as

$$A \sin\left[\frac{2\pi}{C}(t - \lambda)\right] \qquad (16)$$

which is equivalent to the seasonal component in eq. 7. This is true since any linear combination of sine waves of the same period, or frequency, but with different phase shifts is also a sine wave with the same period, or frequency, but a different phase shift. This can be expressed mathematically as

$$a \sin x + b \cos x = \sqrt{a^2 + b^2}\sin(x + \phi)$$

If $a \geq 0$ then

$$\phi = \arcsin\left(\frac{b}{\sqrt{a^2 + b^2}}\right)$$

Since θ_2 and θ_3 are greater than or equal to 0, in eq. 16 $A = \sqrt{a^2 + b^2}$, $C = 1$, and $\lambda = -\frac{\phi}{2\pi}$. For males, $A_{male} = 1.22$, $\phi = 1.15$, and $\lambda_{male} = -0.183$. For females, $A_{female} = 0.770$, $\phi = 1.08$, and $\lambda_{female} = -0.172$. The parameter λ represents what direction and by how much a sine wave of this amplitude needs to be shifted, relative to the y axis, to represent the seasonal curve. The parameter A is the amplitude of the sine wave representing the seasonal variation in growth rate. Growth for *M. plebejus* peaks on the 25th and 29th of January (i.e., summer) for males and females, respectively, and reaches a minimum on the 27th and 31st of July (i.e., winter) for male and female prawns, respectively (Fig. 3).

Fig. 3. Estimated seasonal growth curves for male (solid line) and female (dashed line) eastern king prawns at 25°S latitude. Estimates for

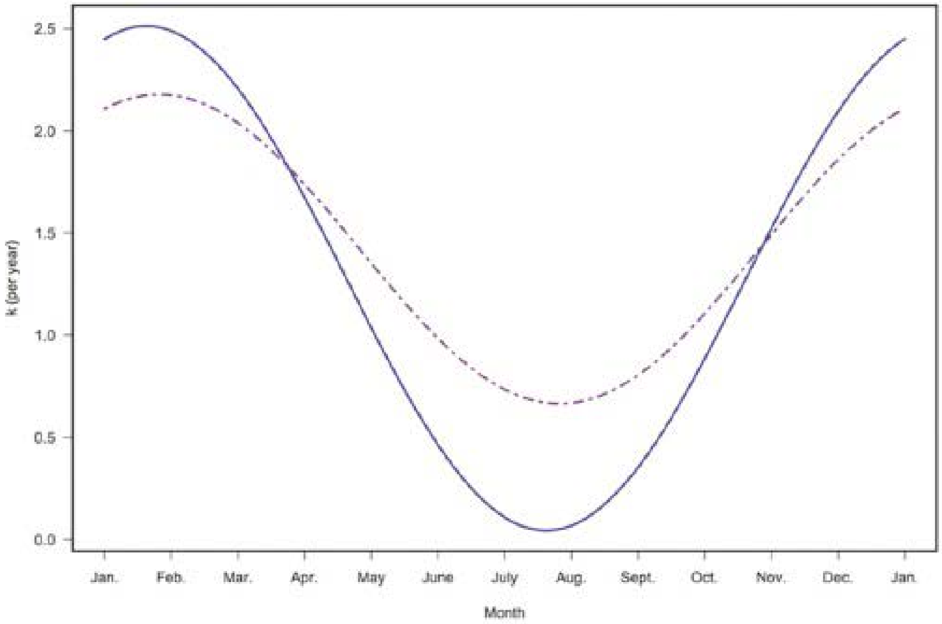
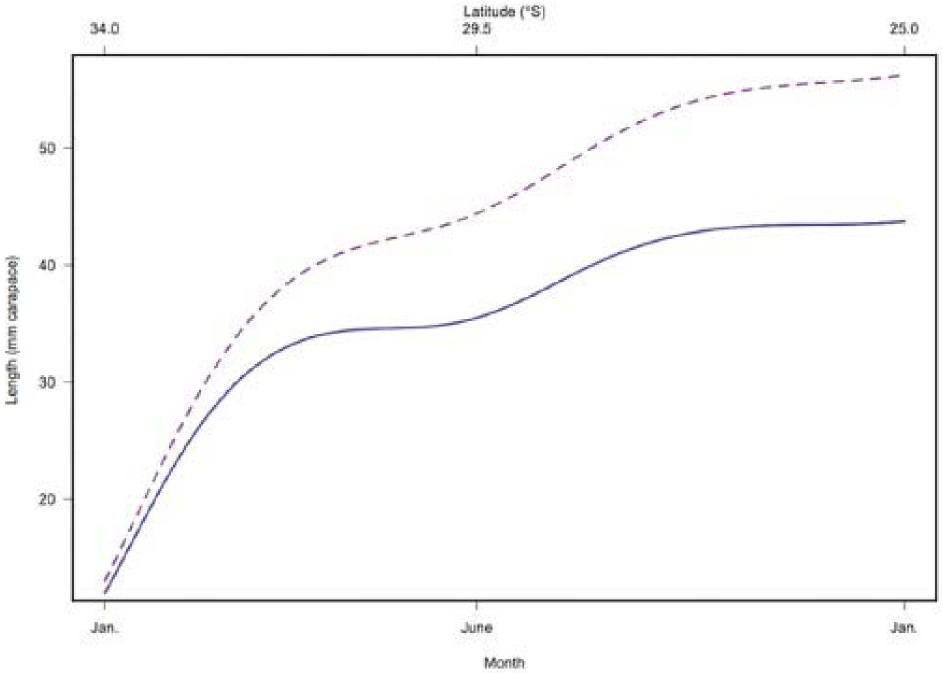


Fig. 4. Theoretical von Bertalanffy growth curves for male (solid line) and female (dashed line) eastern king prawns, incorporating a seasonal and latitudinal change. Movement is shown between 34°S and 25°S over 330 days with l_0 = 17 mm carapace.



The two growth link functions $\overline{d}$ at = 25°S for males and females are

$$(17)\quad g(\boldsymbol{\theta}, t) = 1.43 - 0.0236[d(t) - 25] + 1.11\cos(2\pi t) + 0.499\sin(2\pi t) \quad \text{(male)}$$

$$(18)\quad g(\boldsymbol{\theta}, t) = 1.46 - 0.0556[d(t) - 25] + 0.679\cos(2\pi t) + 0.362\sin(2\pi t) \quad \text{(female)}$$

Equations 17 and 18 can be used to investigate the growth at a particular latitude (fixed $d(t)$) or for a hypothesized latitudinal movement of *M. plebejus* (Fig. 3). To illustrate a further use for these functions (eqs. 17 and 18), we followed the mean of a female *M. plebejus* population from their nursery grounds in New South Wales (34°S) to Fraser Island (25°S), a migration taking approximately 330 days. The migration interval is the approximate average time taken by those animals that showed the greatest migration (>5° movement). The curves assume that migration begins in January, which is not the case for all animals. Assuming this interpolation is adequate, a mean initial CL of 17 mm (with some distribution) was chosen. The *M. plebejus* population follows a linear northerly route, growing with a von Bertalanffy growth curve of the following nature:

$$l_j = l_0 + (l_\infty - l_0)\{1 - \exp[-z(t_1, t_2)]\}$$

arriving off the coast of Fraser Island with a mean length of 56.2 mm CL. The mean of the *M. plebejus* population followed a von Bertalanffy growth curve, growing more rapidly in the months between November and April, with a dramatic slowing of growth in opposing months (Fig. 4). It is noted that a similar calculation can be done for that of the male population.

Discussion

The concept of accounting for extra information via generalized estimating equations was applied to eastern king prawn data. The method quantified how growth changes with respect to latitudinal and seasonal change for different sexes. The inclusion of the latitudinal effect is of particular application to fisheries that require knowledge of growth over a range of latitudes. The eastern king prawn fishery, which extends over much of the Australian eastern continental shelf, is one such fishery. However, breeding habits, food sources, preferred habitat, and many other factors could play a role in a species' growth rate. Influences such as these may be explored further with this method.

However, studies have shown that ectotherms such as the Australian eastern king prawn usually grow to bigger final sizes when reared in cooler conditions (Atkinson and Sibly 1997; Brunel and Dickey-Collas 2010; Bělehrádek and Mann 1935). Life history analysis suggests that it is adaptive for adults to be smaller if reared in conditions that slow down juvenile growth. However, it is usually observed that adults grow to be larger if growth is limited by temperature (Atkinson and Sibly 1997). This idea is closely linked with the negative correlation between the mean von Bertalanffy growth parameters l_∞ and k.

Helser and Lai (2004) presented a Baysian hierachical method that also allowed the calculation of correlations with a latitudinal interaction. They noticed that l_∞ and ln k decline with increasing northerly latitudes. Pilling et al. (2002) pointed out that in practice few studies present direct evidence that these parameters are actually negatively correlated. Although there are exceptions (Hart and Chute 2009), the literature generally suggests that these values lie between –0.8 and –0.9. The current study has shown that for the eastern king prawn, k decreases with an increase in latitude, as seen in the study of Helser and Lai (2004). Incorporating knowledge of how l_∞ varies with latitude would be an interesting extension of this method.

The reasons for the temperature size rule remain enigmatic, but the link between fecundity and body size is an underpinning factor. Reproductive events are generally less frequent in colder environments; therefore, natural selection could favour a larger body size to enhance fecundity at each reproductive episode. Furthermore, a larger asymptotic size could enable individuals to produce larger offspring or to provide better parental care (Angilletta et al. 2004). These ideas may be relevant to eastern king prawns. For example, the relationship between fecundity and size (Courtney et al. 1995) indicates that the larger sizes attained by female eastern king prawns in lower latitudes results in higher egg production compared with their counterparts found further south. Furthermore, the proportion of females with mature and ripe stage ovaries declines with increasing latitude (Montgomery et al. 2007). The higher growth rate associated with migrating northwards appears to be associated with increased reproductive output. Hence, the northerly migration undertaken by eastern king prawns may be a driving force for natural selection, which results in reproductive benefit for this species.

Yamahira and Conover (2002) demonstrated genetically based latitudinal variation in reaction norms for growth in response to temperature. The predominant form of latitudinal adaptation both within and among species was shown to be a countergradient response to length of the growing season. Northern forms (Northern Hemisphere) accelerate growth more rapidly with temperature than do those from the south. This is most likely caused by an adaptation to the length of the growing season. Short growing seasons and long winters in the north favour genotypes with the capacity for rapid summer growth (Yamahira and Conover 2002). The seasonal analysis for eastern king prawns shows that males and females have large differences. Male growth is more variable (A_{male} = 1.22) than female growth (A_{female} = 0.770) and begins earlier (λ_{male} = –0.183) than for females (λ_{female} = –0.172).

Incorporating the effect of latitude into the von Bertalanffy growth model via an application of the work of Wang (1999) has created some key points of difference to the current literature. Using the von Bertalanffy model preserves the biological basis for growth prediction. Using estimating functions allows for simple implementation from small mark–recapture data sets and guarantees asymptotically consistent and unbiased estimates for both growth and additional covariate parameters. The estimating functions do not require distributional assumptions, take into account varying L_∞, and allow other stochastic or unexplained error sources. Once the parameters are estimated, the link function determines the growth allowing for extra analyses to be done, as demonstrated herein. This allows for seasonal curves to be calculated at any latitude, which is particularly useful when stock assessment takes migration into consideration. In this method, growth is not averaged over space or time, as in methods such as Fabens (1965) or even that of James (1991), resulting in more accurate estimates. These analyses must be carried out tentatively, as there are underlying assumptions about what the estimates mean. For example, we assumed that the growth function represents the mean of the population rather than that of an individual.

The importance of a statistically insignificant latitudinal effect for males is dubious. The fact that the parameter is not significant does not mean there is no latitudinal effect. The nonsignificance may be due to the effect being smaller than that of females, therefore placing greater emphasis on variance estimation. For males, the coefficient of variation was estimated from less information-rich data compared with females, with a mean change in latitude of 0.134° for males compared with 0.156° for females, approximately 16% more information. There are also approximately 23% more recaptures for females compared with males. Recent unpublished mark–recapture results on *M. plebejus* from its most northern distribution indicate sexual differences, with females moving longer average distances, at higher speeds, higher recapture rates, and shorter periods-at-liberty than males. One hypothesis for this is that females are required to develop ovaries, which leads to greater ingestion of food and lipoproteins, making them more vulnerable to capture. Another hypothesis is that males have higher rates of natural mortality than females, thus dying at a younger age, and therefore resulting in fewer recaptures. In Queensland, females dominate the greater depths (i.e., >150 m), and it may be that males, being smaller, are just not designed for the greater depth habitats, possibly because of the higher pressures. This may inhibit their migration–movement to greater depths.

It is well known in prawn biology and prawn fisheries that prawns move from shallow to deep water as they grow (Glaister et al. 1987; Ruello 1975). There are also some reports that some species actually move back into shallow waters to overwinter in rivers (i.e., banana prawns, Penaeus merguiensis) or actually move into shallower waters after spawning (Crocos and Kerr 1983). However, the overwhelming data indicate "shallow to deep" overall movement. It is hypothesized that eastern king prawns are trying to follow depth contours, rather than trying to migrate eastward. The complex shape of the eastern Australian continental shelf strongly affects the longitudinal movement of the prawns.

To explain the longitudinal movement, one needs an understanding of the continental shelf and the shelf edge or "shoulder". From southern (33°S) to northern (28°S) New South Wales, the continental shelf is quite narrow and is most narrow around Byron Bay (≈29°S), where the shelf is about ≈70 km wide. The shelf edge runs parallel to the coast in a northeasterly direction. Thus, as the New South Wales prawns migrate north along depth contours, they move in a northeasterly direction. Once north of Byron Bay (29°S), the continental shelf shoulder runs north–south to Fraser Island (25°S), then north of Fraser Island (25°S) to Lady Elliot and Musgrave Islands (23°S), where the shelf shoulder turns and runs northwest. Hence, it is found that a higher proportion of Queensland tagged prawns move westward. Given this, the longitudinal change present, which is predominantly eastward, is likely to be heavily influenced by (i) the prawns choosing to follow depth contours as they grow and move northwards and (ii) the shape of the eastern Australian continental shelf and the shelf edge. Therefore, an attempt to quantify this movement into deeper water is difficult to model with longitude alone. This and the relatively small change in longitude present in the data are the primary reasons why longitude was left out of the final model for the eastern king prawn.

Knowledge of the true movement from New South Wales with respect to path taken, time to migrate along this path, reasons for migration (ocean currents), effects of additional covariates, and implications for fishery management need to be better understood to make full use of the results and model. We have some insight into the true movement of *M. plebejus*, which is south to north. However, knowledge of the true path taken (perhaps parabolic) could prove the linear interpolation to be a gross assumption. It is clear, however, that the general movement is north, with less northerly movement for Queensland prawns. The introduction of additional covariates such as depth would be an excellent extension of this method, but it is noted that a large, well-planned data set would be required to detect the influences of these covariates. The inclusion of temperature as a covariate would be a natural extension of this method, but determining how it shall be included will depend heavily on the data and species being studied.

Acknowledgements

The authors gratefully acknowledge the reviewers, whose comments have improved the paper substantially.

References

Angilletta, M.J., Jr, Steury, T.D., and Sears, M.W. 2004. Temperature, growth rate, and body size in ectotherms: fitting pieces of a life-history puzzle. Integr. Comp. Biol. 44(6): 498–509. doi:10.1093/icb/44.6.498. PMID:21676736.

Ashton, K.G. 2004. Sensitivity of intraspecific latitudinal clines of body size for tetrapods to sampling, latitude and body size. Integr. Comp. Biol. 44(6): 403–412. doi:10.1093/icb/44.6.403. PMID:21676726.

Atkinson, D., and Sibly, R.M. 1997. Why are organisms usually bigger in colder environments? Making sense of a life history puzzle. Trends Ecol. Evol. 12(6): 235–239. doi:10.1016/S0169-5347(97)01058-6. PMID:21238056.

Bělehrádek, J., and Mann, S.E. 1935. Temperature and living matter: with 70 illustrations. Vol. 8. Gebrüder Borntraeger, Berlin, Germany.

Brunel, T., and Dickey-Collas, M. 2010. Effects of temperature and population density on von Bertalanffy growth parameters in Atlantic herring: a macro-ecological analysis. Mar. Ecol. Prog. Ser. 405: 15–28. doi:10.3354/meps08491.

Chen, Y., Jackson, D.A., and Harvey, H.H. 1992. A comparison of von Bertalanffy and polynomial functions in modelling fish growth data. Can. J. Fish. Aquat. Sci. 49(6): 1228–1235. doi:10.1139/f92-138.

Courtney, A.J., Montgomery, S.S., Die, D.J., Andrew, N.L., Cosgrove, M.G., and Blount, C. 1995. Maturation in the female eastern king prawn Penaeus plebejus from coastal waters of eastern Australia, and considerations for quantifying egg production in penaeid prawns. Mar. Biol. (Berl.), 122(4): 547–556. doi:10.1007/BF00350677.

Courtney, A.J., Haddy, J.A., Campbell, M.J., Roy, D.P., Tonks, M.L., Gaddes, S.W., Chilcott, K.E., O'Neill, M.F., Brown, I.W., McLennan, M., Jebreen, E.J., van der Geest, C., Rose, C., Kistle, S., Turnbull, C.T., Kyne, P.M., Bennett, M.B., and Taylor, J. 2007. Bycatch weight, composition and preliminary estimates of the impact of bycatch reduction devices in Queensland's trawl fishery. Fisheries Research and Development Corporation (FRDC), Brisbane, Qld.

Crocos, P.J., and Kerr, J.D. 1983. Maturation and spawning of the banana prawn Penaeus merguiensis de Man (Crustacea: Penaeidae) in the Gulf of Carpentaria, Australia. J. Exp. Mar. Biol. Ecol. 69(1): 37–59. doi:10.1016/0022-0981(83)90171-5.

Emiliani, D.A. 1971. Equipment for holding and releasing penaeid shrimp during marking experiments. Fish Bull. 69(1): 247–250.

Fabens, A.J. 1965. Properties and fitting of the von Bertalanffy growth curve. Growth, 29(3): 265–289. PMID:5865688.

Geist, V. 1987. Bergmann's rule is invalid. Can. J. Zool. 65(4): 1035–1038. doi:10.1139/z87-164.

Glaister, J.P., Lau, T., and McDonall, V.C. 1987. Growth and migration of tagged eastern Australian king prawns, Penaeus plebejus Hess. Mar. Freshw. Res. 38(2): 225–241. doi:10.1071/MF9870225.

Haddon, M. 2011. Modelling and quantitative methods in fisheries. 2nd ed. CRC Press–Chapman and Hall Group, Boca Raton, Fla.
Hampton, J. 1986. Effect of tagging on the condition of southern bluefin tuna, Thunnus maccoyii (Castlenau). Mar. Freshw. Res. 37(6): 699–705. doi:10.1071/MF9860699.
Hart, D.R., and Chute, A.S. 2009. Estimating von Bertalanffy growth parameters from growth increment data using a linear mixed-effects model, with an application to the sea scallop Placopecten magellanicus. ICES J. Mar. Sci. 66(10): 2165–2175. doi:10.1093/icesjms/fsp188.
Helser, T.E., and Lai, H.-L. 2004. A Bayesian hierarchical meta-analysis of fish growth: with an example for North American largemouth bass, Micropterus salmoides. Ecol. Model. 178(3–4): 399–416. doi:10.1016/j.ecolmodel.2004.02.013.
James, I.R. 1991. Estimation of von Bertalanffy growth curve parameters from recapture data. Biometrics, 47(4): 1519–1530. doi:10.2307/2532403.
Montgomery, S.S. 1990. Movements of juvenile eastern king prawns, Penaeus plebejus, and identification of stock along the east coast of Australia. Fish. Res. 9(3): 189–208. doi:10.1016/S0165-7836(05)80001-3.
Montgomery, S.S., Courtney, A.J., Blount, C., Stewart, J., Die, D.J., Cosgrove, M., and O'Neill, M.F. 2007. Patterns in the distribution and abundance of female eastern king prawns, *Melicertus plebejus* (Hess, 1865), capable of spawning and reproductive potential in waters off eastern Australia. Fish. Res. 88(1–3): 80–87. doi:10.1016/j.fishres.2007.08.002.
O'Neill, M.F., Courtney, A.J., Good, N.M., Turnbull, C.T., Yeomans, K.M., Staunton-Smith, J., and Shootingstar, C. 2005. Reference point management and the role of catch-per-unit effort in prawn and scallop fisheries. Tech. Rep. Fisheries Research and Development Corporation (FRDC), Brisbane, Qld.
Partridge, L., and French, V. 1996. Thermal evolution of ectotherm body size: why get big in the cold? In Animals and temperature: phenotypic and evolutionary adaptation. Society for Experimental Biology Semnar Series No. 59. Edited by I.A. Johnson and A.F. Bennett. Cambridge University Press, UK. pp. 265–292. doi:10.1017/CBO9780511721854.012.
Pauly, D., and Gaschutz, G. 1979. A simple method for fitting oscillating length growth data, with a program for pocket calculators. ICES CM, 6: 24–26.
Pilling, G.M., Kirkwood, G.P., and Walker, S.G. 2002. An improved method for estimating individual growth variability in fish, and the correlation between von Bertalanffy growth parameters. Can. J. Fish. Aquat. Sci. 59(3): 424–432. doi:10.1139/f02-022.
Pitcher, T.J., and MacDonald, P.D.M. 1973. Two models for seasonal growth in fishes. J. Appl. Ecol. 10(2): 599–606. doi:10.2307/2402304.
Quinn, T.J., and Deriso, R.B. 1999. Quantitative fish dynamics (biological resource management). Oxford University Press, New York.
Rijnsdorp, A.D., and Pastoors, M.A. 1995. Modelling the spatial dynamics and fisheries of North Sea plaice (Pleuronectes platessa L.) based on tagging data. ICES J. Mar. Sci. 52(6): 963–980. doi:10.1006/jmsc.1995.0092.
Ruello, N.V. 1975. Geographical distribution, growth and breeding migration of the eastern Australian king prawn Penaeus plebejus Hess. Mar. Freshw. Res. 26(3): 343–354. doi:10.1071/MF9750343.
Shepherd, S.A., and Hearn, W.S. 1983. Studies on Southern Australian abalone (genus Haliotis). IV. Growth of H. laevigata and H. ruber. Mar. Freshw. Res. 34(3): 461–475. doi:10.1071/MF9830461.
Sheridan, P.F., Patella, F.J., Jr, Baxter, N., and Emiliani, D.A. 1987. Movements of brown shrimp, Penaeus aztecus, and pink shrimp, P. duorarum, relative to the US–Mexico border in the western Gulf of Mexico. Mar. Fish. Rev. 49: 14–19.
Somers, I.F., and Kirkwood, G.P. 1984. Movements of tagged tiger prawns, Penaeus spp., in the western Gulf of Carpentaria. Mar. Freshw. Res. 35(6): 713–723. doi:10.1071/MF9840713.
Wang, Y. 1998. Theory and methods: growth curves with explanatory variables and estimation of the effect of tagging. Australian and New Zealand Journal of Statistics, 40(3): 299–304. doi:10.1111/1467-842X.00034.
Wang, Y.G. 1999. Estimating equations for parameters in stochastic growth models from tag–recapture data. Biometrics, 55(3): 900–903. doi:10.1111/j.0006-341X.1999.00900.x. PMID:11315025.
Wang, Y.G., and Die, D. 1996. Stock–recruitment relationships of the tiger prawns (Penaeus esculentus and Penaeus semisulcatus) in the Australian northern prawn fishery. Mar. Freshw. Res. 47(1): 87–95. doi:10.1071/MF9960087.
Wang, Y.G., and Somers, I.F. 1996. A simple method for estimating growth parameters from multiple length–frequency data in presence of continuous recruitment. Fish. Res. 28(1): 45–56. doi:10.1016/0165-7836(96)00484-5.
Wang, Y.G., and Thomas, M.R. 1995. Accounting for individual variability in the von Bertalanffy growth model. Can. J. Fish. Aquat. Sci. 52(7): 1368–1375. doi:10.1139/f95-132.
Xiao, Y. 1999. General age- and time-dependent growth models for animals. Fish Bull. 97(3): 690–701.
Yamahira, K., and Conover, D.O. 2002. Intra- vs. interspecific latitudinal variation in growth: adaptation to temperature or seasonality? Ecology, 83(5): 1252–1262. doi:10.1890/0012-9658(2002)083[1252:IVILVI]2.0.CO;2.

Appendix A. Asymptotic variance

To simplify the calculation, we represent the estimating functions in matrix form.

Let

$$
\begin{aligned}
\mathbf{S} &= \left(\frac{\delta d_i}{2} - \bar{d}, \ldots, \frac{\delta d_n}{2} - \bar{d}\right) \\
\mathbf{Q} &= \left\{\frac{1}{2\pi}[\sin(2\pi t_{i2}) - \sin(2\pi t_{i1})], \ldots, \frac{1}{2\pi}[\sin(2\pi t_{n2}) - \sin(2\pi t_{n1})]\right\} \\
\mathbf{R} &= \left\{\frac{-1}{2\pi}[\cos(2\pi t_{i2}) - \cos(2\pi t_{i1})], \ldots, \frac{-1}{2\pi}[\cos(2\pi t_{n2}) - \cos(2\pi t_{n1})]\right\} \\
\mathbf{T} &= (T_1, \ldots, T_n) \\
\boldsymbol{\theta} &= (k, \theta_1, \theta_2, \theta_3) \\
\boldsymbol{\beta} &= (\mathbf{T},\ \mathbf{ST},\ \mathbf{Q},\ \mathbf{R})
\end{aligned}
$$

where ST represents component-wise multiplication, and b is an n × 4 matrix. We can now represent h more succinctly:

$$\boldsymbol{\eta} = (\mathbf{L}_\infty - \mathbf{L}_1)[1 - \exp(-\boldsymbol{\theta}\beta')] - \Delta\mathbf{L}$$

where $\Delta\mathbf{L} = \mathbf{L}_2 - \mathbf{L}_1$. Now the estimating functions can be represented in the following way. Let

$$
\begin{aligned}
\mathbf{C} &= [(1,\ 1,\ 1, \ldots,\ 1), \mathbf{T},\ \mathbf{ST},\ 2\pi\mathbf{Q},\ -2\pi\mathbf{R}]' \\
\mathbf{f} &= \boldsymbol{\eta}\mathbf{C}
\end{aligned}
$$

To complete the asymptotic variance calculation, we need the design matrix $\mathbf{D_g}$. Let

$$X_i = \eta_i \begin{pmatrix} 1 \\ T_i \\ S_iT_i \\ Q_i \\ R_i \end{pmatrix}$$

$$\mathbf{D_g} = \sum_i X_i X_i^T = \begin{pmatrix} \mathbf{1} \\ \mathbf{T} \\ \mathbf{ST} \\ \mathbf{Q} \\ \mathbf{R} \end{pmatrix} \boldsymbol{\eta\eta}'(\mathbf{1\,T\,ST\,Q\,R}) = \sum_i \eta_i^2 \begin{pmatrix} 1 & T_i & S_iT_i & Q_i & R_i \\ T_i & T_i^2 & S_iT_i^2 & Q_iT_i & R_iT_i \\ S_iT_i & S_iT_i^2 & S_i^2T_i^2 & S_iT_iQ_i & S_iT_iR_i \\ Q_i & Q_iT_i\,\mathrm{R_i\ T} & Q_iS_iT_i & Q_i^2 & Q_iR_i \\ R_i & R_iT_i & R_iS_iT_i & R_iQ_i & R_i^2 \end{pmatrix}$$

and $\mathbf{F}$ the Jacobian

$$\mathbf{F} = \begin{pmatrix} \frac{\partial f_0}{\partial k} & \frac{\partial f_0}{\partial l_\infty} & \frac{\partial f_0}{\partial \theta_1} & \frac{\partial f_0}{\partial \theta_2} & \frac{\partial f_0}{\partial \theta_3} \\ \frac{\partial f_1}{\partial k} & \frac{\partial f_1}{\partial l_\infty} & \frac{\partial f_1}{\partial \theta_1} & \frac{\partial f_1}{\partial \theta_2} & \frac{\partial f_1}{\partial \theta_3} \\ \frac{\partial f_2}{\partial k} & \frac{\partial f_2}{\partial l_\infty} & \frac{\partial f_2}{\partial \theta_1} & \frac{\partial f_2}{\partial \theta_2} & \frac{\partial f_2}{\partial \theta_3} \\ \frac{\partial f_3}{\partial k} & \frac{\partial f_3}{\partial l_\infty} & \frac{\partial f_3}{\partial \theta_1} & \frac{\partial f_3}{\partial \theta_2} & \frac{\partial f_3}{\partial \theta_3} \\ \frac{\partial f_4}{\partial k} & \frac{\partial f_4}{\partial l_\infty} & \frac{\partial f_4}{\partial \theta_1} & \frac{\partial f_4}{\partial \theta_2} & \frac{\partial f_4}{\partial \theta_3} \end{pmatrix} = \begin{pmatrix} \mathbf{1} \\ \mathbf{T} \\ \mathbf{ST} \\ \mathbf{Q} \\ \mathbf{R} \end{pmatrix} \nabla \mathbf{f}_0$$

Let

$$z = kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i$$
$$f_0 = \sum_i \eta_i = \sum_i (l_\infty - L_{1_i})[1 - \exp(-z_i)] - (L_{2_i} - L_{1_i})$$
$$f_1 = \sum_i \eta_i T_i = \sum_i T_i\{(l_\infty - L_{1_i})[1 - \exp(-z_i)] - (L_{2_i} - L_{1_i})\}$$
$$f_2 = \sum_i \eta_i S_i T_i = \sum_i S_i T_i\{(l_\infty - L_{1_i})[1 - \exp(-z_i)] - (L_{2_i} - L_{1_i})\}$$
$$f_3 = \sum_i Q_i = \{(l_\infty - L_{1_i})[1 - \exp(-z_i)] - (L_{2_i} - L_{1_i})\}$$
$$f_4 = \sum_i R_i = \{(l_\infty - L_{1_i})[1 - \exp(-z_i)] - (L_{2_i} - L_{1_i})\}$$

Letting and, the derivatives with respect to the parameter set form the gradient of f_0. The derivatives are as follows:

$$\frac{\partial f_0}{\partial k} = \sum_i \frac{\partial}{\partial k} B - B\exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)] - A = \sum_i T_i B \exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)]$$
$$\frac{\partial f_0}{\partial l_\infty} = \sum_i \frac{\partial}{\partial l_\infty} l_\infty - L_{1_i} - (l_\infty - L_{1_i})\exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)] - A = \sum_i 1 - \exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)]$$
$$\frac{\partial f_0}{\partial \theta_1} = \sum_i \frac{\partial}{\partial \theta} B - B\exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)] - A = \sum_i B T_i S_i \exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)]$$
$$\frac{\partial f_0}{\partial \theta_2} = \sum_i \frac{\partial}{\partial \theta} B - B\exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)] - A = \sum_i B Q_i \exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)]$$
$$\frac{\partial f_0}{\partial \theta_3} = \sum_i \frac{\partial}{\partial \theta} B - B\exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)] - A = \sum_i B R_i \exp[-(kT_i + \theta_1 T_i S_i + \theta_2 Q_i - \theta_3 R_i)]$$

The other rows of the Jacobian matrix are scalars of these derivatives by *Ti, SiTi, Qi, and Ri,* respectively. The standard errors for the latitudinal effect can be found by solving the following equation. According to Maritz (1995), the covariance matrix is estimated by

$$\mathbf{C} = \mathbf{F}^{-1}\mathbf{D}_g(\mathbf{F}')^{-1}$$

and the standard errors equal sqrt[diag(***C***)]. . The correlations are the standard Pearson correlations that can be calculated from the covariance matrix.

Reference

Maritz, J. 1995. Distribution-free statistical methods. Chapman & Hall–CRC, London, England.

Appendix B. Derivation of d(t)

The proposed link function to characterize the latitudinal effect is

$$g(\theta, t) = k + \theta[d(t) - \bar{d}]$$

where k is the proposed maximum at, and d(t) is the latitude at some time *t*. Lai and Kimura (2002) transformed latitudes d_1 and d_2 in the link function into Euclidian distances departing from the reference latitude. They did this to account for spatial variability in survey sampling for sea scallops. The latitude at some time *t* will be the linear interpolation of the form

$$d(t) = d_1 + \frac{d_2 - d_1}{t_2 - t_1}(t - t_1)$$

To implement a similar method to Wang (1999), we need to integrate over the time at liberty to obtain *z(t1, t2)* (eq. 14). The constant d is also added to correct for the range in which the latitude in the data set is defined. Letting $d_2 - d_1 = d$ and adding the seasonal components to the model the integral becomes

$$
\begin{aligned}
z(t_1, t_2) &= \int_{t_1}^{t_2} k + \theta_1 \left[d_1 + \frac{\Delta d}{t_2 - t_1}(t - t_1) - \bar{d} \right] + \theta_2 \cos(2\pi t) + \theta_3 \sin(2\pi t)\, dt \\
&= \left[kt + \theta_1 d_1 t + \theta_1 \frac{\Delta d}{t_2 - t_1} \frac{t^2}{2} - \theta_1 \frac{\Delta d}{t_2 - t_1} t t_1 - t\bar{d} + \frac{\theta_2}{2\pi} \sin(2\pi t) - \frac{\theta_3}{2\pi} \cos(2\pi t) \right]_{t_1}^{t_2} \\
&= k(t_2 - t_1) + \theta_1 (t_2 - t_1) \left(\frac{d_1 + d_2}{2} - \bar{d} \right) + \frac{\theta_2}{2\pi} [\sin(2\pi t_2) - \sin(2\pi t_1)] - \frac{\theta_3}{2\pi} [\cos(2\pi t_2) - \cos(2\pi t_1)]
\end{aligned}
$$

Reference

Lai, H.-L, and Kimura, D.K. 2002. Analyzing survey experiments having spatial variability with an application to a sea scallop fishing experiment. Fish. Res. 56(3): 239–259. doi:10.1016/S0165-7836(01)00323-X.

Published by NRC Research Press