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

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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. Bioeconomic 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 standardization, economic indicators, management strategy evaluation, prawns, spatial stock assessment.

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 1). The otter trawl fishery harvests ~ 3000 t 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 (>90 m) off Queensland as individuals grow to spawning size (Montgomery *et al.*, 2007; Lloyd-Jones *et al.*, 2012; Braccini *et al.*, 2012b). In 2010, ∼ 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 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 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 (Pascoe *et al.*, 2013; Dichmont *et al.*, 2013). In order to improve fishing profits, additional management measures were discussed, including further effort control and 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 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 2).

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 for indicating 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 (NSW Department of Primary Industries, 2010; Fisheries Queensland, 2013). 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.

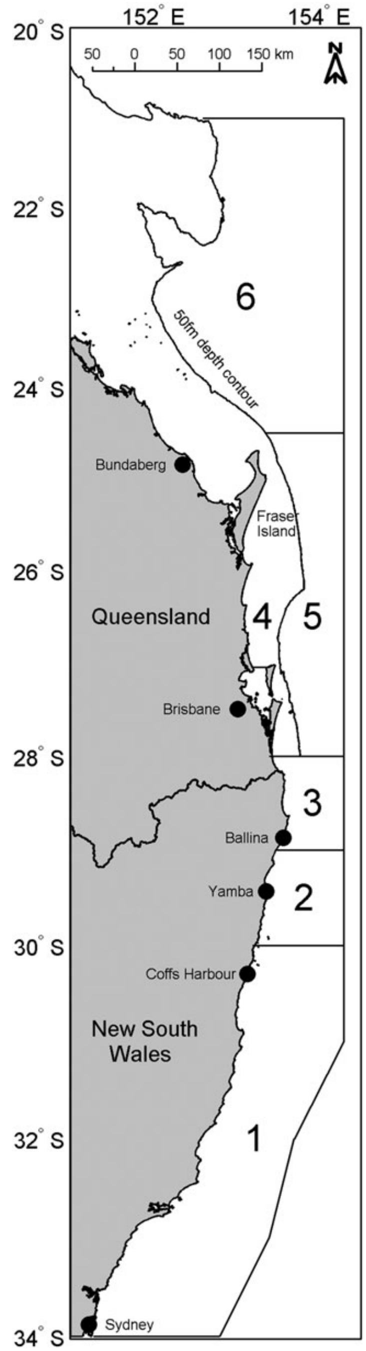

Figure 1. Map of the Australian eastern king prawn fishery zoned by analysis regions 1 to 6. Queensland region 4 covered water depths less than 50 fathom (≈90 m) and excluded pre-oceanic-recruits from estuaries, Moreton Bay (adjacent to Brisbane) and Fraser Island north. Queensland regions 5 and 6 covered water depths equal to or greater than 50 fathom. 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.

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).

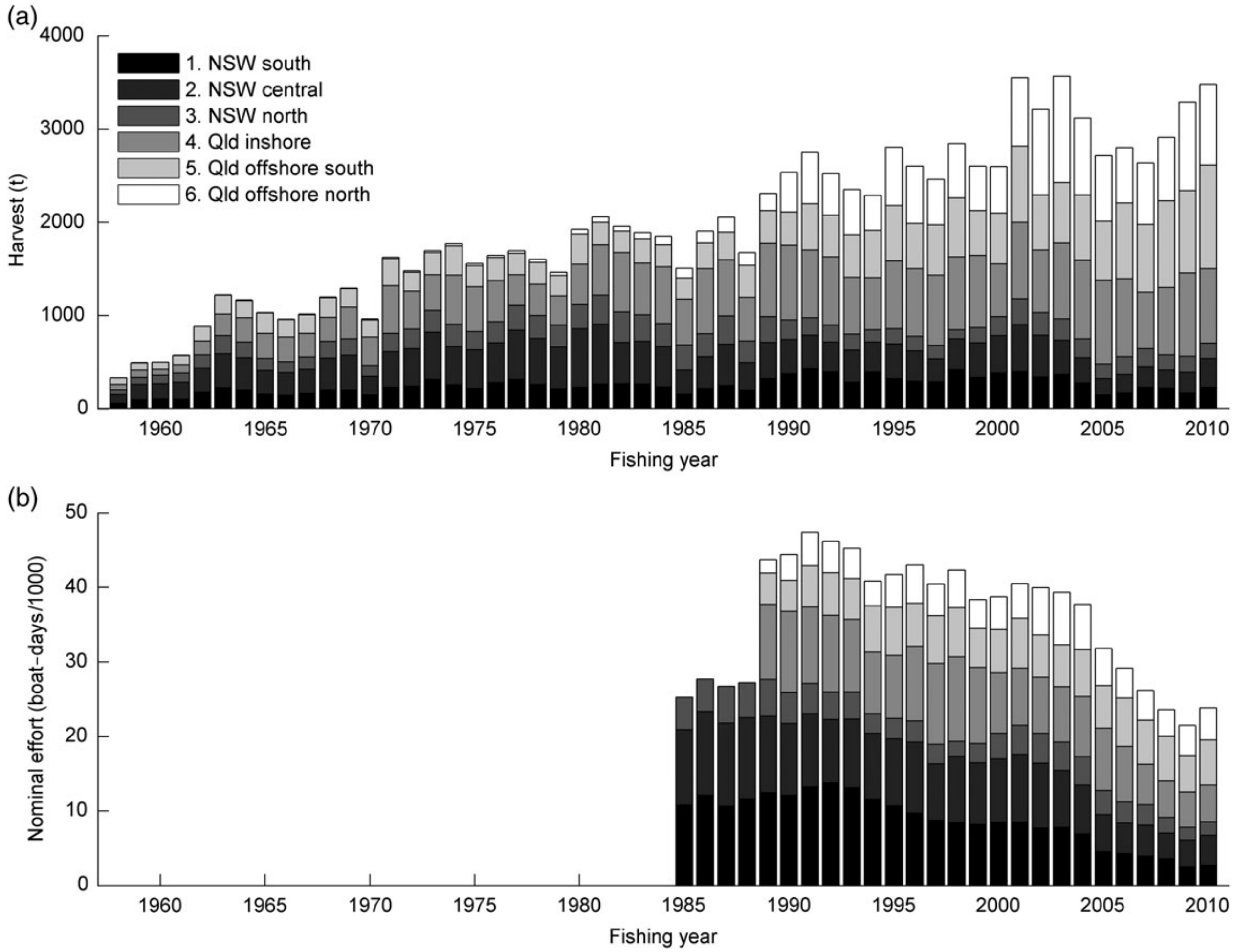

Figure 2. Summary fishery statistics for eastern king prawn (**a**) harvest, and (**b**) fishing effort from New South Wales (NSW) and Queensland (Qld) waters. No records on total fishing effort were available before 1985 and 1989 fishing years from NSW and Qld, respectively.

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.

Methods

Commercial harvest data

Data were stratified by six fishing regions across New South Wales (NSW) and Queensland (Qld) State waters (Figure 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, (~ 90 m), water depths, between 21°S and 28°S], (5) Qld Offshore South (≥ 50 fathom water depths, between 24.5°S and 28°S), and (6) Qld Offshore North (≥ 50 fathom 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 1900s. Harvests were small (< 200 t) until the 1950s, and we assumed year 1958 to be the commencement of significant fishing mortality.

Monthly harvests from 1958–2010 were reconstructed from four data sources: (i) NSW monthly fisher catch returns from 1958–1983, (ii) NSW monthly commercial logbooks from 1984–2010, (iii) Queensland Fish Board annual records from 1958–1980, and (iv) Queensland daily commercial logbooks 1988–2010.

NSW prawn harvest records from 1958–1978 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 1900–1957, 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 1958–1978 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 1958–1980 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 1989–2010, 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 1958–1980 and 1989–2010 annual estimates (adjusted $R^2 = 0.86$). Queensland EKP landings from 1958–1988 were expanded regionally and monthly based on Poisson generalized linear modelling of harvest patterns using 1989–1994 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 1958–1988.

Standardized commercial catch rates

Three catch rate analyses were conducted on New South Wales and Queensland logbook data (Table 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 × 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 1/4 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 $\mathbf{Z}_2$.

Table 1. Linear mixed models (REML) used to standardize catch rates from New South Wales (NSW) and Queensland (QLD).

Analysis 1	**QLD: regions 4–6 and years 1989–2010.**
Response:	$\log(\text{kgs boat} - \text{day}^{-1})$
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:	$\mathbf{Z}_1\boldsymbol{\gamma}_1 + \mathbf{Z}_2\gamma_2$
Offset:	—
Predictions:	$\boldsymbol{\beta}_1$
Analysis 2	**QLD: regions 4–6 and years 1969–1988.**
Response:	$\log(\text{kgs boat} - \text{day}^{-1})$
Fixed terms:	$\beta_0 + \mathbf{X}_1\boldsymbol{\beta}_1 + \mathbf{X}_3\boldsymbol{\beta}_3 + \mathbf{X}_4\beta_4$
Random terms:	$\mathbf{Z}_1\boldsymbol{\gamma}_1 + \mathbf{Z}_2\gamma_2$
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 1–3 and years 1984–2010.**
Response:	$\log(\text{kgs boat} - \text{month}^{-1})$
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 $\mathbf{X}_2$ were not available. Therefore the $\boldsymbol{\beta}_2$ fishing power effect was not estimated but was inserted as an offset (Table 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 1969–1988 (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).

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.

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; Fisheries Queensland, 2007; Courtney *et al.*, 2012).

Individual beam trawl catches, measured in numbers of prawns, were analysed using a Poisson generalized linear model with log link and estimated dispersion (McCullagh and Nelder, 1989; GenStat, 2011). 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.

Size composition data

Two datasets on size structure were used: (i) carapace length frequencies and (ii) commercial size-grade frequencies. Together, these two datasets 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 5-kg 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) $> 30\ \text{lb}^{-1} \approx$ 1–27 mm carapace length, (2) 21–30 $\text{lb}^{-1} \approx$ 28–33 mm, (3) 16–20 $\text{lb}^{-1} \approx$ 34–37 mm, (4) 10–15 $\text{lb}^{-1} \approx$ 38–43 mm, (5) 8–10 $\text{lb}^{-1} \approx$ 44–47 mm, (6) 6–8 $\text{lb}^{-1} \approx$ 48–53 mm and (7) $<6\ \text{lb}^{-1} \approx$ 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).

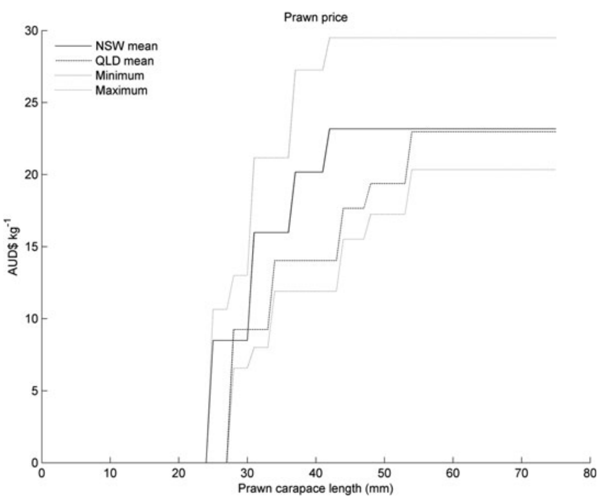

Figure 3. Mean eastern king prawn landing-prices (AUD\$ kg^{-1}) by prawn length and State. The minimum and maximum values indicate monthly variation, with higher prices around December and lower prices around June.

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 3). The average by-product value per boat day by region (Table 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.

Vessel cost parameters (means and variances), other than fuel, were based on questionnaire responses from 24 vessel owners from the Queensland fishery (Table 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 (O'Neill and Leigh, 2007; Braccini *et al.*, 2012a). For example, the average vessel length was 17.0 m for the sample vs. 17.5 m 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 (O'Neill and Leigh, 2007; Braccini *et al.*, 2012a) 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 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 ($\bar{B}_r^{by}$: \$ 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.

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) (Tables 3 and 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 1958–2010, 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 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 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.*, 2012).

Economic model and parameters

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

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

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

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

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

Table 3. Equations used for simulating EKP population dynamics (for notation, Table 4).

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

Table 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	$p_{4\to6} = p_{4\to5}\dfrac{\exp(\rho)}{1+\exp(\rho)}$, where ρ was an estimated logit variable.	Transition probability matrix (6 × 6) 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*.
Ξ	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 (Sadovy *et al.*, 2007; O'Neill *et al.*, 2010; Punt *et al.*, 2010). 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 millimetre.
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 2007–2010. 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: $l_{50} = 38; l_{95} = 45$ 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. The schedule was estimated using binomial regression and logit link, $m \sim$ 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).
Estimated	$n = 76$	The values and their variances and covariances 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 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 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 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 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 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 0.13–0.35, 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 6). ζ were the 52 estimated parameters known as barycentric or simplex coordinates, distributed *NID*(0, σ) with number nparRresid = number of recruitment years – 1 (Möbius, 1827; Sklyarenko, 2011). **e** was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill *et al.*, 2011).

Continued

Table 4. *Continued*

Model parameters	Equations, values and errors	Notes
$q_r^f(t)$ and q_4^s	$q_r^f(t) = \exp\left(\log(q_r^f) - \varsigma(\cos(t) + \vartheta_r \sin(t))/\sqrt{1+\vartheta_r^2}\right)$ $t = 2\pi$ seqmonth/12	Fishery catchability was based on a sinusoidal function to model monthly patterns using the variable 'seqmonth'. As the maximum water temperature was in February, seqmonth = 1 in March and = 12 in February. The equation 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 midmonth biomass form2 (Table 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 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 $-\sum\frac{1}{2}(\tilde{n}-1)\left(\log\nu - \nu/\hat{\nu}\right)$, 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 (O'Neill *et al.*, 2011)	(10)
Preventing unrealistically large population estimates and low estimates of harvest rate: $0.5\left(\frac{\tilde{u} - \max(CN_y/R_y)}{\sigma}\right)^2 b$, 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 $\max(CN_y/R_y) < \tilde{u}$. The penalty was applied between 1992 and 2010.	Optimization penalty (Hall and Watson, 2000)	(11)

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

$$\pi_y = \sum_r\left(\sum_t\left(\sum_l v_{r,t,l}C_{r,t,l} - \Omega^{\mathrm{V}}_{r,t}\right) + \bar{B}_r^{by}(1-c_L)E_{r,y} - \left(\Omega^{\mathrm{F}}_{r,y}\frac{E_{r,y}}{\bar{d}_r}\rho\right)\right)$$

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 3), $C_{r,t,l}$ was the EKP harvest weight, $\Omega^{\mathrm{V}}_{r,t}$ was the total variable costs, $\bar{B}_r^{by}$ was the average by-product value ($) taken each boat day, c_L was the share of the catch paid to crew members (a labour cost), $E_{r,y}$ was the total annual boat days fished, $\Omega^{\mathrm{F}}_{r,y}$ 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 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 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 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.

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 2011–2020, 1000 multivariate length-spatial parameter estimates were created from the MCMC covariance matrix. For economics, 1000 random variations on Table 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 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 $\mathrm{E}_{\mathrm{MEYfv}}$ ($\bar{d}$). Procedures 6 to 9 used regional MSY and $\mathrm{MEY}_{\mathrm{v}}$ catch rate control rules to manage total fishing efforts of $\mathrm{E}_{\mathrm{MSY}}$ and $\mathrm{E}_{\mathrm{MEYfv}}$ ($\bar{d}$).

In addition, the management procedures were replicated in two scenarios: (A) 1–9 under 2010 fishing costs and fishing power, and (B) 10–18 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.

For management procedures 6 to 9 (Table 7), closures for different areas were calculated based on catch rate thresholds:

$$\mathrm{m_r} = \text{first month } \left(c^{\mathrm{f}}_{\mathrm{r,m}} < c^{\mathrm{limit}}_{\mathrm{r,m}}\right) + 1,$$

where $c^{\mathrm{f}}_{\mathrm{r,m}}$ was the fishery standardized catch rate (kg) for region r and month m, $cr^{\mathrm{limit}}_{\mathrm{r,m}}$ was the standardized catch rate reference point for either MSY or $\mathrm{MEY}_{\mathrm{v}}$, 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

Table 6. Negative log-likelihood functions for parameter bounds and distributions.

-LL functions for:	Equation
Stock recruitment steepness *h*:	(12)
$0.5\left(\frac{\mathrm{logit}(h)-\mathrm{logit}(0.5)}{\sigma}\right)^2$, where $\sigma = 0.7$ defined a broad prior distribution.	
Instantaneous natural mortality *M* month^{-1}:	(13)
$0.5\left(\frac{M-0.2}{\sigma}\right)^2$, where $\sigma = 0.05$ defined the prior distribution ≅ 28% CV.	
Annual log recruitment deviates η_y:	(14)
$\frac{n}{2}\left(\log(2\pi) + 2\log(\sigma) + (\hat{\sigma}/\sigma)^2\right)$, or simplified as $n\left(\log\sigma + \frac{1}{2}(\hat{\sigma}/\sigma)^2\right)$, where $\sigma = \min(\max(\hat{\sigma}, \sigma_{\min}), \sigma_{\max})$, $\sigma_{\min} = 0.1$ and $\sigma_{\max} = 0.4$ specified bounds, $\hat{\sigma} = \sqrt{\sum \eta_y^2/n}$ and *n* was the number of recruitment years *y*.	

Table 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, $\sum \approx 30\,000$	Qld (area 4)	Oct (12)
2. Close NSW southern and Qld inshore waters in January.	Max last five years, $\sum \approx 30\,000$	NSW (area 1) Qld (area 4)	Jan (3)
3. Close Qld waters in January.	Max last five years, $\sum \approx 30\,000$	Qld waters (areas 4 to 6)	Jan (3)
4. Close all NSW and Qld waters in January.	Max last five years, $\sum \approx 30\,000$	All waters (areas 1 to 6)	Jan (3)
5. Limit total effort to $\mathrm{E}_{\mathrm{MEYfv}}$, and close all waters in January.	$\mathrm{E}_{\mathrm{MEYfv}} \approx 8000$	All waters (areas 1 to 6)	Jan (3)
6. Limit total effort to $\mathrm{E}_{\mathrm{MSY}}$, and close regional waters on MSY catch rate thresholds.	$\mathrm{E}_{\mathrm{MSY}} \approx 38\,000$	Variable	$\mathrm{m_r}$ to Oct (12)
7. Limit total effort to $\mathrm{E}_{\mathrm{MEYfv}}$ and close regional waters on MSY catch rate thresholds.	$\mathrm{E}_{\mathrm{MEYfv}} \approx 8000$	Variable	$\mathrm{m_r}$ to Oct (12)
8. Limit total effort to $\mathrm{E}_{\mathrm{MSY}}$, and close regional waters on $\mathrm{MEY}_{\mathrm{v}}$ catch rate thresholds.	$\mathrm{E}_{\mathrm{MSY}} \approx 38\,000$	Variable	$\mathrm{m_r}$ to Oct (12)
9. Limit total effort to $\mathrm{E}_{\mathrm{MEYfv}}$ and close regional waters on $\mathrm{MEY}_{\mathrm{v}}$ catch rate thresholds.	$\mathrm{E}_{\mathrm{MEYfv}} \approx 8000$	Variable	$\mathrm{m_r}$ to Oct (12)

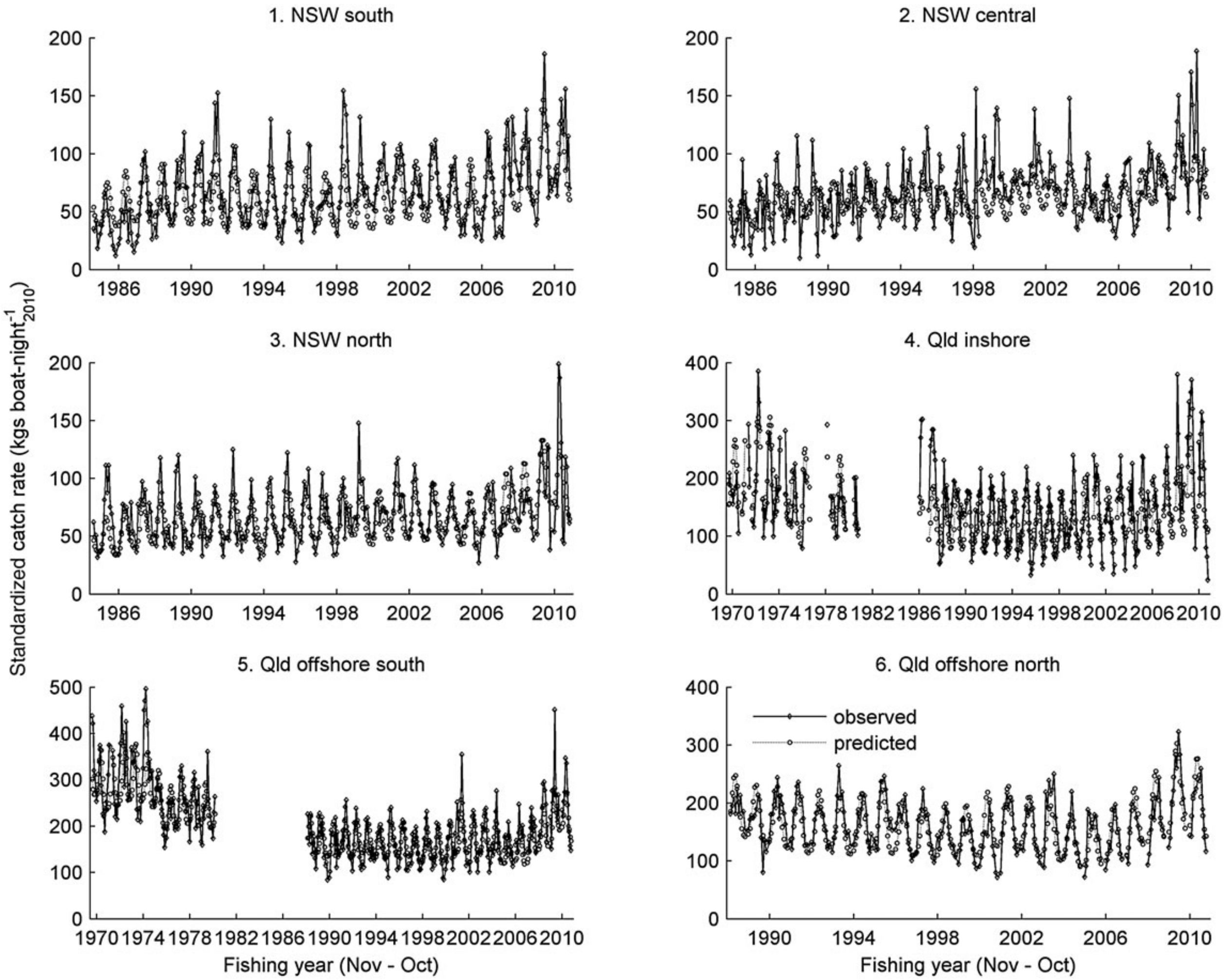

Figure 4. Eastern king prawn observed (standardized) and model-predicted catch rates for each spatial region and month.

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.

Results

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.

The model fitted the EKP fishery standardized catch rates relatively well, although region 2 EKP catch rates were less seasonal and less predictable (Figure 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 with 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 (Figures 5 and 6). For region 6 where large EKP were caught, the model predicted the grading data very well (Figure 6).

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 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 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 0.184 month^{-1}.

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 MSY and MEY are presented in Table 9. The MEY results were highly dependent on the specified economic parameters, listed in Table 2. The variability in MEY was tabulated for the average number of days currently fished per boat per year

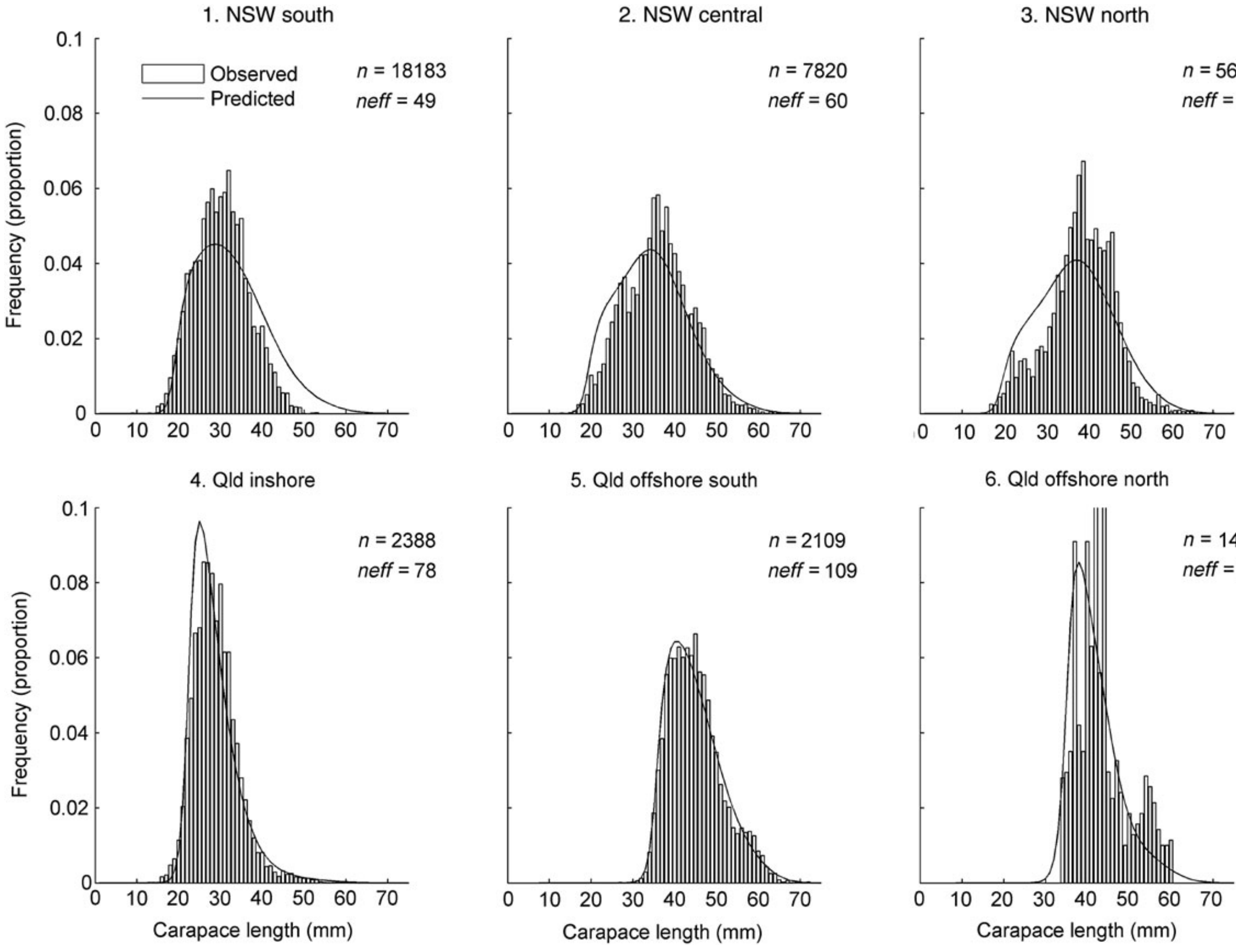

Figure 5. Eastern king prawn observed and model-predicted harvest length frequencies for each region. The plot frequencies were summed over sexes and by effective sample numbers for the months with available data. Mean number of prawns measured (*n*) and effective numbers (*neff*) per sex and month are shown.

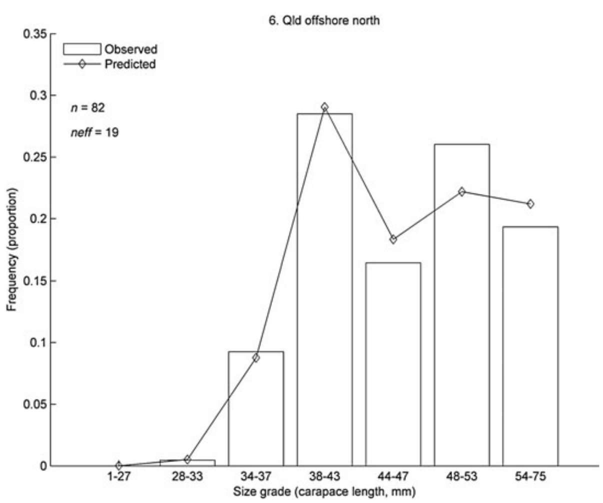

Figure 6. Eastern king prawn observed and model-predicted frequencies of harvest size grading data from Queensland offshore north waters (region 6). The plot frequencies were summed by effective sample numbers over 136 monthly prawn-size-box frequencies. Mean sample number of 5-kg boxes graded (*n*) and effective numbers (*neff*) per month shown.

($\bar{d}$, Table 2), twice this number ($2\bar{d}$) and for variable costs only (Table 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 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.

Simulation of management procedures

The results of simulating management procedures were as follows (see Figure 8 and the probabilities of catch-rate control rules closing fishing regions, plotted in Figure 9):

Table 8. Parameter estimates and standard errors for the model calibration $(-\log l = -3253.7; \sigma_r = 0.115)$.

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

Table 9. Estimated management quantities (95% confidence intervals) for the model calibration.

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} $(\bar{d})$	1253 (641:1854)	1453 (905:1949)
MEY_{vf} $(2\bar{d})$	1909 (1497:2273)	1962 (1564:2324)
MEY_v	2521 (2176:2828)	2470 (2121:2806)
Annual fishing effort (boat-days)		
E_{MSY}	38 002 (27 035:50 754)	28 300 (20 110:37 663)
E_{MEYvf} $(\bar{d})$	7470 (3577:11158)	6667 (3970:9531)
E_{MEYvf} $(2\bar{d})$	12 869 (9425:16467)	9972 (7501:12565)
E_{MEYv}	19 892 (15 552:24 049)	14 307 (10 977:17 676)

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 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).

Management procedures 1 to 4 *(maximum $E_{status\text{-}quo} \approx$ 30 000 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 ~ 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.

Management procedure 5 *($E_{MEYfv} \approx$ 8000 boat-days year^{-1})*

- Compared with 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 ~ 1300 t.
- Reduced fishing effort provided larger overall profit but smaller total harvest.

Management procedure 6 *($E_{MSY} \approx$ 38 000 boat-days year^{-1} and $CPUE_{MSY}$ control rules)*

- Compared with 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.

Management procedure 7 *($E_{MEYfv} \approx$ 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 with procedures 1 to 4.
- Annual harvests were more than halved at ~ 1300 t from 8000 boat-days.
- The probabilities of regional closures were substantially less compared with procedure 6 using E_{MSY}. Regions 1 and 4 had nearly a 20% chance of closure after June. The probabilities were < 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 with procedure 5.

Management procedure 8 *($E_{MSY} \approx$ 38 000 boat-days year^{-1} and $CPUE_{MEYv}$ control rules)*

- Compared with 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 ~ 1600 t, and total effort was managed at ~ 13 000 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 *($E_{MEYfv} \approx$ 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).

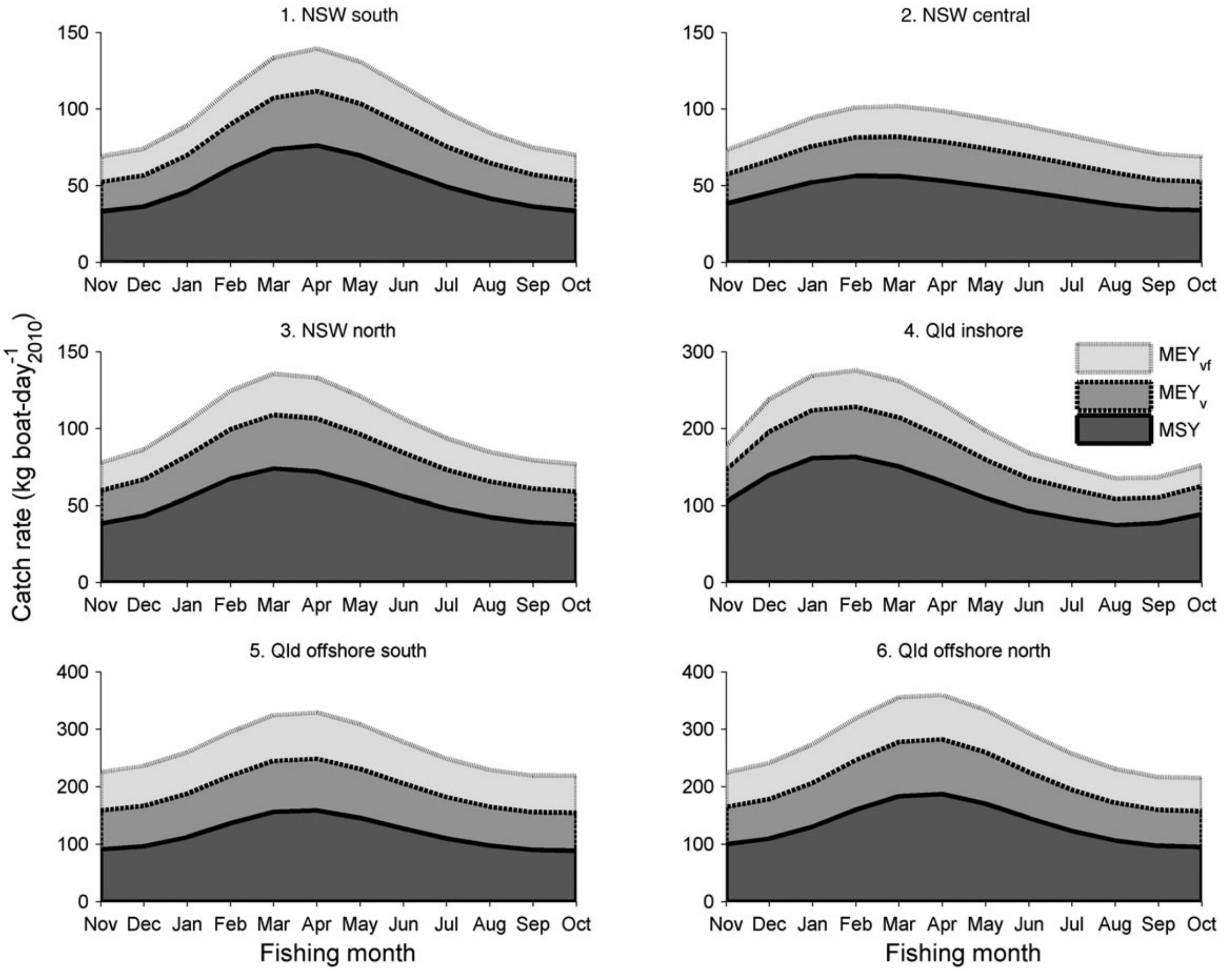

Figure 7. Mean monthly catch rate targets for maximum sustainable yield (MSY), maximum economic yield for variable costs (MEY$_v$) and MEY$_{vf}$ ($\bar{d}$) for variable plus fixed costs by fishing region. Catch rates were standardized to 2010 fishing power.

- Compared with procedures 1 to 4, relative profit was ~ 50% higher.
- Annual harvests were the lowest of all management procedures, at about 1100 t, with ~ 6000 boat-days effort.
- The closure probabilities were higher compared with 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.

Discussion

The results provide a major advance over the previous assessment (O'Neill *et al.*, 2005; Ives and Scandol, 2007), 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 sustainable and more profitable.

Our stock steepness estimate of 0.36 (Table 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 0.26–0.36 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 with O'Neill *et al.* (2005) and Ives and Scandol (2007), allowed more accurate estimates of EKP productivity.

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

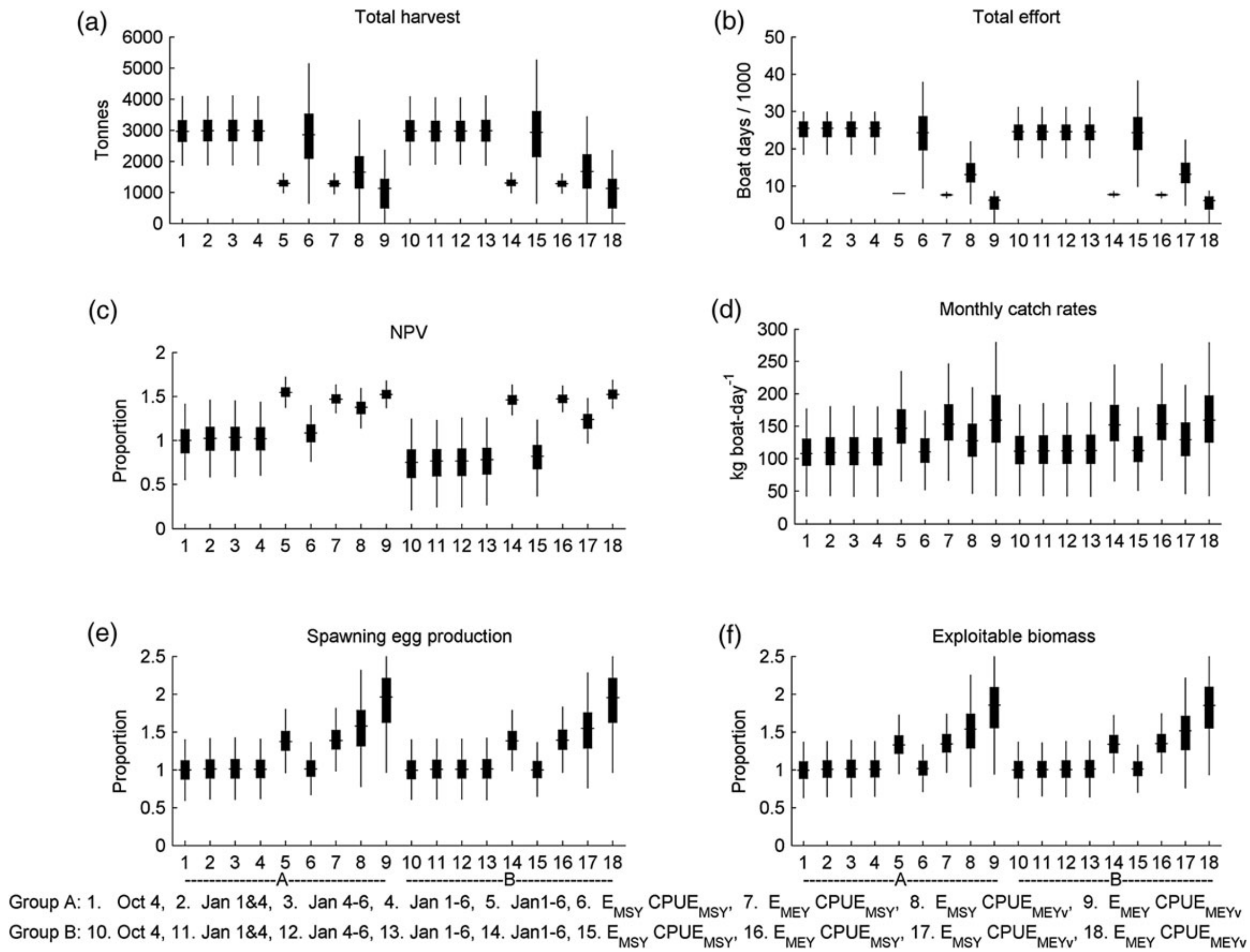

Figure 8. Performance measures over ten future years for nine different EKP management procedures (Table 7); boxes 1 – 9 are for scenario A (2010 costs and fishing power) and 10 – 18 scenario B (3% increases in both costs and fishing power). The first row of plots (**a**) and (**b**) represented industry 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 ~95% coverage of the simulations.

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 midyear.

The setting of the catch-rate trigger required knowledge of where and when EKP were abundant and information on profitable catch rates (Figure 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 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).

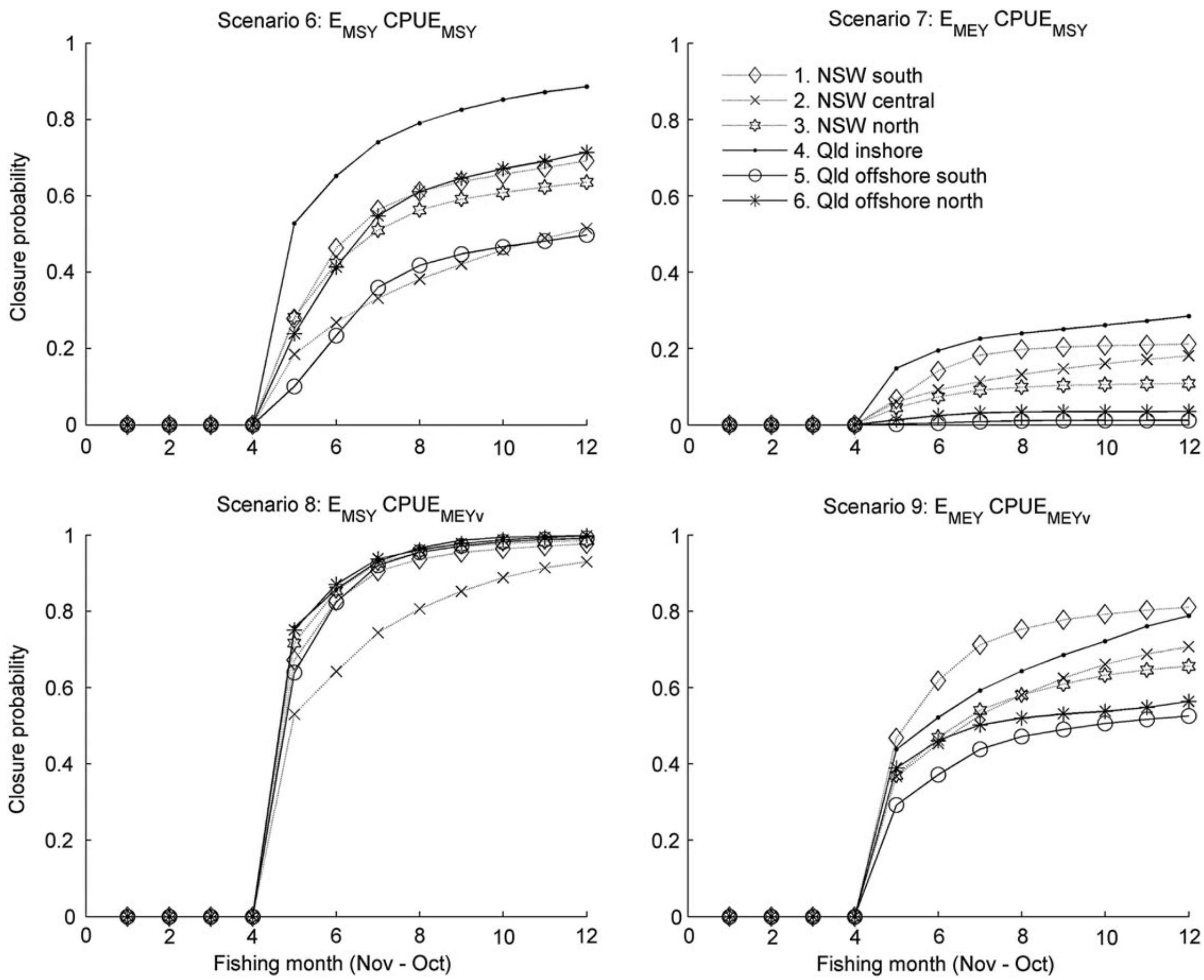

Figure 9. Regional closure probabilities for management performance using catch-rate reference points.

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 of increasing profit for the fleet as a whole, avoiding excess harvest of small prawns, and improving 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.

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 ~ 3100 t. 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 ~ 28 000 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 overfishing 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 ($\bar{d}$) and fishing power. The ratio of MEY to MSY was especially influenced by the high annual fixed costs (Table 2). The MEY ranged between 1300 t and 2000 t and E_{MEY} between 7000 and 13 000 boat-days. A higher value of $\bar{d}$ significantly increased profit, but reduced the number of vessels, which may negatively impact social objectives of the fishery (Wang and Wang, 2012; Pascoe *et al.*, 2013). 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 ~ 2500 t and E_{MEYv} between 14 000 and 20 000 boat-days per year.

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