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Maximizing profits and conserving stocks in the Australian Northern Prawn Fishery

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The Australian Northern Prawn Fishery (NPF) is one of the few that has adopted a dynamic version of a 'maximum economic yield' (MEY) target, and, on this basis, the fishery is undergoing a process of substantial stock rebuilding. This study details the bioeconomic model used to provide scientific management advice for the NPF, in terms of the amount of allowable total gear length in the fishery, for both the MEY target and the path to MEY. It combines the stock assessment process for two species of tiger prawns with a specification for discounted economic profits, where the harvest function in the profit equation is stock-dependent. Results for the NPF show a substantial 'stock effect', indicating the importance of conserving fish stocks for profitability. MEY thus occurs at a stock size that is larger than that at maximum sustainable yield, leading to a 'win-win' situation for both the industry (added profitability) and the environment (larger fish stocks and lower impact on the ecosystem). Sensitivity results emphasize this effect by showing that the MEY target is much more sensitive to changes in the price of prawns and the cost of fuel, and far less so to the rate of discount.

Key words: Australian Northern Prawn Fishery, bioeconomic modelling, maximum economic yield, stock conservation.

1. Introduction

Many fisheries around the world are characterized by substantial inefficiencies in the form of excessive fishing, fleet overcapitalization, low profits, and stocks of fish that are highly depleted. Part of the solution to these problems is to adopt an appropriate target level of effort or catch, i.e. to maximize profits regardless of changes in prices and costs of fishing, and to implement this target with an instrument that gives industry a rights-based incentive to protect the fishery. The solution that the Australian Northern Prawn Fishery

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(NPF) has adopted is a system of tradable effort units and a newly established, and now fully implemented, target defined by a dynamic version of 'maximum economic yield' (MEY), or a sustainable catch or effort level that maximizes the difference between discounted total revenues and the costs of fishing (e.g., Clark 1990). The NPF, a lucrative multispecies fishery, one of the most profitable in the Australian Fishing Zone, exporting most of its harvest to Japan, thus provides one of the very few examples in the world of a fishery that has adopted MEY as its target and follows a path to MEY.

This paper details the 'real-time' bioeconomic model that is used to provide scientific management advice for the NPF, i.e. the annual effort levels, defined by the total amount of gear allocated to the fishery, both in terms of the MEY target and the path to MEY.[1] It combines the stock assessment process for the major target species (separately for the two species of tiger prawns – grooved and brown tiger prawns; *Penaeus semisulcatus* and *P. esculentus* respectively – and for endeavour prawns as a group), with a specification for profits, where the harvest function in the profit equation is stock-dependent. Unlike previous bioeconomic models for this fishery (e.g., Kompas and Che 2004; Grafton *et al.* 2006), which used a different model for the dynamics of the prawn stocks from that used for management purposes, the new approach combines a state-of-the-art delay-difference model of prawn population dynamics (Dichmont *et al.* 2003) with an integrated profit equation and forward projections for the price of prawns and the cost of fuel.

There is a second related point. Results for the NPF show a substantial 'stock effect' (Hannesson 2007). This adds to the growing body of such effects, at least in the Asia Pacific region (Grafton *et al.* 2007), indicating the importance of conserving fish stocks for profitability. Stock effects occur either when increases in the stock of fish substantially lowers the per-unit cost of fishing, or when harvest increases (with increases in stock size) at any given level of effort. In such cases, as in the NPF, the stock size corresponding to MEY will exceed that at which 'maximum sustainable yield' (MSY) is achieved. In other words, MEY will be 'conservationist', so that stocks at MEY will be larger than at MSY, leading to a 'win-win' for both the industry (added profitability) and the environment (larger fish stocks and lower impacts on the rest of the ecosystem). Sensitivity results show that MEY is much more sensitive to changes in the price of prawns and the cost of fuel, and far less so to the rate of discount. Therefore, the rate of discount has relatively little practical effect on the stock levels corresponding to MEY, unlike traditional models (e.g. Hannesson 1993).

[1] There are relatively few recent examples of bioeconomic models for actual capture fisheries (e.g., Clarke *et al.* 1992; Campbell *et al.* 1993; Horan and Shortle 1999; Bertignac *et al.* 2000; Pascoe *et al.* 2002; Kompas and Che 2006; and Ahmed *et al.* 2007), and fewer still that solve for the transitional path to dynamic MEY.

Section 2 of the paper provides a basic description of the NPF and section 3 outlines the model of population dynamics which forms the basis for the stock assessment. Section 4 details the economic profit equation. Unlike typical bioeconomic models, there is no independent harvest function; rather the harvest function is integrated with the population dynamics model on which the stock assessment is based. Harvest is, however, still a function of effort and the number of prawns, so that any 'stock effect' will appear through the outcomes of the model. As this is an effort-controlled fishery, effort is the control variable, with the effects of changes in stock size appearing in the harvest function and not the cost function. Allowance is made for 'effort creep' (i.e. changes over time in fishing efficiency), so that effort measures are 'standardized' to account for this factor. Section 5 sets out the estimates and projections for key economic parameters and section 6 discusses results. Section 7 provides some concluding remarks.

2. The Australian Northern Prawn Fishery

The NPF extends over close to 1 000 000 km^2 in Northern Australia between Cape Londonderry in Western Australia and Cape York in Queensland, although fishing is mostly confined to the inshore parts of that area. It is a multispecies and multistock fishery, with nine commercial species of prawn. The main species are grooved and brown tiger prawns, and white- and red-legged banana prawns (*P. merguiensis* and *P. indicus* respectively). Four other prawn species (blue endeavour prawns *M. endeavouri*, red endeavour prawns *M. ensis*, red spot king prawn *Melicertus longistylus*, and the blue-leg or western king prawns *Melicertus latisulcatus*) also form an important component of the catch. For the most part, banana prawns are fished in different areas and seasons than tiger prawns and are subject to large environmental and seasonal fluctuations while the tiger, endeavour, and king prawns are caught in similar locations and times. However, king prawns are such a small component of the catch that they are not included in the modelling.

The NPF was established in 1966 and increased rapidly to over 200 vessels in less than 5 years of operation. Vessel numbers have fallen over time with management-imposed decreases in effort (in response in large part to ongoing 'effort creep' in the fishery) (Dichmont *et al.* 2008) and two voluntary vessel buyback programs, the most recent of which (in Dichmont *et al.* 2007) reduced vessel numbers to 52 trawlers. Management decisions for this fishery are made by the Board of the Australian Fisheries Management Authority (AFMA), which is advised by a Management Advisory Committee (MAC) that consists of industry members, a scientist, a representative of AFMA and representatives of the Australian Federal and Queensland State Governments. The MAC, in turn, is advised by a Resource Assessment Group (RAG). The bioeconomic model outlined in this paper forms the basis for the advice on effort levels.

Economic returns in the NPF fluctuate, mostly because of variations in the catch of banana prawns, but this fishery is one of Australia's few fisheries that regularly earns a profit, with average real net returns (not counting management costs) of over $20 million Australia dollars (AUD) annually during the 1990s (Rose and Kompas 2004). Returns have fallen recently with increases in the price of fuel and falls in the price of prawns (as a result of relatively inexpensive aquaculture prawns entering the market and an appreciation of the Australian dollar). The fleet is strictly commercial in orientation and established a MEY target in 2004, with formal implementation of the target in place for the 2008 season. Most of the catch (often more than 90 per cent) is sold in Japan.

Although there has been a stochastic frontier study of the banana prawn fishery (Kompas *et al.* 2004), based mostly on economic and logbook data, there is no formal stock assessment for banana prawns and therefore no basis to define a stock-recruitment relationship. In contrast, tiger prawns are both more stable and more predictable than banana prawns. Management of the NPF in the past has been heavily influenced by the assessed over-exploitation of tiger prawns. However, these species are assessed to have recovered to the stock size at which MSY is achieved and are hence no longer considered over-exploited (BRS 2007). Management of the fishery is accomplished through seasonal and area closures (along with a daytime ban on tiger prawn fishing), and an effort control in the form of a limit on the amount of headrope length for the fishery as a whole. The amount of gear in the fishery is based on the most recent stock assessment, with an additional restriction that prawn trawlers can only tow twin or quad nets. Fishers have statutory rights and are allowed to trade gear units.

Over time, it has become clear that tiger prawn stocks have been reduced substantially by fishing (with brown tiger prawns of special concern) and the fishery has worked aggressively to rebuild stocks over the past decade, first to the stock size at which MSY is achieved, and now towards an MEY target. The reduction in effort is reflected in logbook data (AFMA 2008), with continuous falls in nominal fishing effort since 1999 (Table 1) and comparable reductions in 'standardized effort' (standardized effort differs from nominal effort as it accounts for the impact of 'effort creep'; Bishop *et al.* 2008). Nevertheless, remaining economic inefficiency and potential future 'effort creep' continues to be a concern and the fishery is now contemplating a move to an ITQ system (combined with setting a total allowable catch) using a dynamic bioeconomic assessment to further protect stocks and maximize returns.

3. Population dynamics and stock assessment

Tiger prawns have been the focus for quantitative stock assessments and management measures for many years in the NPF (Somers 1990; Wang and Die 1996; Somers and Wang 1997; Dichmont *et al.* 2001, 2003),

Table 1 Catch, nominal effort (boat days), totals, and total standardized effort in the NPF (1993–2007)

Year	Catch (tonnes)		Nominal effort (boat days)		Totals		Total standardized effort	
	Grooved	Brown	Effort grooved	Effort brown	Tiger catch	Total effort	Standard effort	Standard CPUE
1993	1325	1208	9097	7320	2533	16417	16417	154
1994	1841	1318	10492	8101	3159	18593	19808	160
1995	1674	2465	8468	8295	4139	16763	18947	218
1996	1193	1155	9555	7138	2348	16693	18992	124
1997	1451	1253	8991	6353	2704	15344	18397	147
1998	1835	1450	10962	6920	3285	17882	22283	147
1999	1417	753	8948	4223	2170	13171	16483	132
2000	1585	634	8756	3873	2219	12629	15269	145
2001	1478	530	8042	2626	2009	10668	13650	147
2002	1757	260	7889	975	2017	8864	11100	182
2003	1950	310	7786	653	2260	8439	10568	214
2004	1506	259	7369	500	1765	7869	9697	182
2005	1302	445	6287	1623	1748	7910	9254	189
2006	1306	550	5350	1775	1857	7125	8317	223
2007	895	303	3957	1185	1197	5142	6266	191

Source: AFMA (2008).

owing to the perception that these species can be recruitment overfished. The approach used to estimate historical recruitments and indices of spawning stock size is currently based on a variant of the delay-difference model developed by Deriso (1980) and Schnute (1985). This model has been expanded to include endeavour prawns (two species modelled together, with the biological parameters for the endeavour group based on those for blue endeavour prawns as this species dominates the catch and is the only one for which the basic biology is known). The model includes two fleets (those targeting brown and grooved tiger prawns), which leads to technical interactions between the two tiger species and the two endeavour species because, for example, fishing targeted at brown tiger prawns leads to catches of all four species.

This model operates on a weekly time-step and allows spawning and recruitment to the fishable population to occur each week. Allowance is also made for weekly changes in availability. Following Dichmont *et al.* (2003), the dynamics of the recruited biomass and recruited numbers for each assessed species (or species group) are governed using the equations:

$$B_{y,w+1} = (1+\rho)\, B_{y,w}\, e^{-Z_{y,w}} - \rho\, e^{-Z_{y,w}} \left(B_{y,w-1}\, e^{-Z_{y,w-1}} + W_{k-1}\, \alpha_{w-1}\, R_{\tilde{y}(y,w-1)}\right) + W_k\, \alpha_w\, R_{\tilde{y}(y,w)} \qquad (1)$$

and

$$\tilde{N}_{y,w+1} = \tilde{N}_{y,w}\, e^{-Z_{y,w}} + \alpha_w\, R_{\tilde{y}(y,w)} \tag{2}$$

where $\tilde{N}_{y,w}$ is the number of recruited prawns (of both sexes) at the start of week w of year y; $B_{y,w}$ is the biomass of recruited prawns (of both sexes) at the start of week w of year y; $Z_{y,w}$ is the total mortality during week w of year y, so that:

$$Z_{y,w} = M + F_{y,w} \tag{3}$$

α_w is the fraction of the annual recruitment that occurs during week w (assumed to be independent of year and sex); M is the instantaneous rate of natural mortality (assumed to be independent of sex and age); $F_{y,w}$ is the fishing mortality during week w of year y; R_y is the recruitment during 'biological year' y; $\tilde{y}(y, w)$ is the 'biological year' corresponding to week w of year y:

$$\tilde{y}(y,w) = \begin{cases} y & w < 40 \\ y+1 & \text{otherwise} \end{cases} \tag{4}$$

ρ is the Brody growth coefficient (Ricker 1975); $W_{k\text{-}1}$ is the average weight of a prawn the week before it recruits (in week k) to the fishery; and W_k is the average weight of a prawn when it recruits to the fishery.

Equation (3) is understood such that the 'biological year' ranges from week 40 (roughly the start of October) until week 39 (roughly the end of September). This choice is based on recruitment index data from surveys (Somers and Wang 1997).

Fishing mortality during week w of year y, $F_{y,w}$, includes contributions from the two fleets, changes over time in fishing efficiency, and changes over the year in availability, so that:

$$F_{y,w} = A_w\, \gamma_{y,w}\, (q_G E^G_{y,w} + q_B E^B_{y,w}) \tag{5}$$

where $E^G_{y,w}$ is the effort during week w of year y targeted towards grooved tiger prawns; $E^B_{y,w}$ is the effort during week w of year y targeted towards brown tiger prawns; q_G is the catchability coefficient for the grooved tiger prawn fleet; q_B is the catchability coefficient for the brown tiger prawn fleet; A_w is the relative availability during week w; and $\gamma_{y,w}$ is the relative efficiency during week w of year y (Bishop *et al.* 2008).

The values for the bulk of the parameters of the model (Table 2) are assumed known based on auxiliary and prior information (see Dichmont *et al.* 2003). The values for the parameters that are not prespecified (i.e., the annual recruitments for 1970 to the present) are obtained by minimizing an objective function involving the catch-in-weight data.

The spawner stock size index for calendar year y, S_y, is given by:

Table 2 The values assumed for the parameters of the population dynamics model that are based on auxiliary information (source (unless stated otherwise): Dichmont *et al*. 2003)

Quantity	Grooved tiger prawns	Brown tiger prawns	Endeavour prawns
Catchability for Grooved tiger prawn fleet, q_G	0.000088	0.000008	0.000083
Catchability for brown tiger prawn fleet, q_B	0.000011	0.000088	0.000205
Brody growth coefficient, ρ	0.979	0.982	0.968
Length-at-recruitment	Males: 26 mm Females: 28 mm	Males: 26 mm Females: 28 mm	Males: 27 mm Females: 26 mm
Length-weight regression (Males)	Intercept: 0.002659 Power: 2.6480	Intercept: 0.003739 Power: 2.5739	Intercept: 0.001709 Power: 2.7775
Length-weight regression (Females)	Intercept: 0.00195500 Power: 2.7460	Intercept: 0.002078 Power: 2.7645	Intercept: 0.001392 Power: 2.8565
Rate of natural mortality, M	0.045 per week	0.045 per week	0.045 per week

$$S_y = \sum_w \beta_w \frac{1 - e^{-Z_{y,w}}}{Z_{y,w}} \tilde{N}_{y,w} \tag{6}$$

The catch during week w of year y (in mass), $H_{y,w}$, is given by:

$$H_{y,w} = B_{y,w} \frac{F_{y,w}}{Z_{y,w}} (1 - e^{-Z_{y,w}}) \tag{7}$$

Recruitment for (future) biological year $y + 1$ is assumed to be related to S_y according to a Ricker stock-recruitment relationship:

$$\hat{R}_{y+1} = \tilde{\alpha} S_y \, e^{-\tilde{\beta} S_y} \tag{8}$$

where $\hat{R}_y$ is the conditional mean for the recruitment during biological year y (i.e. the recruitment from October of year y−1 to September of year y) based on the stock-recruitment relationship, and $\tilde{\alpha}$, $\tilde{\beta}$ are the parameters of the stock-recruitment relationship. The relationship between the actual recruitment and the conditional mean based on the stock-recruitment relationship is given by:

$$R_y = \hat{R}_y \, e^{\eta_y} \quad \eta_{y+1} = \rho_r \eta_y + \sqrt{1 - \rho_r^2} \xi_{y+1} \quad \xi_{y+1} \sim N(0; \sigma_r^2) \tag{9}$$

where ρ_r is the environmentally driven temporal correlation in recruitment, and σ_r is the (environmental) variability in recruitment about the stock-recruitment relationship. Estimation of the four parameters of the stock-recruitment relationship ($\tilde{\alpha}$, $\tilde{\beta}$, ρ_r and σ_r) involves minimizing an objective function, which includes the temporal correlation among recruitments because of environmental fluctuations and the uncertainty associated with the estimates of each annual recruitment (see Dichmont *et al.* (2003) for further details). Uncertainty is represented through bootstrap simulations.

4. Discounted profit and maximum economic yield

The population dynamics model is augmented by a profit equation that measures the difference between the discounted total costs and revenues from fishing, with a harvest function that incorporates the biological connection between different levels of harvest or fishing effort (by species) and stock size. The profit equation takes the form:

$$\sum_{t>y_{\text{cur}}} \pi_y = \beta_y \sum_w \left\{ \sum_s \left[v^s_{y,w} H^s_{y,w} - (c_L v^s_{y,w} H^s_{y,w} + c_M H^s_{y,w}) \right] - \sum_f \left[c_K E^f_{y,w} + c_F E^f_{y,w} \right] \right\} \tag{10}$$

where π_y is the profit in future year y; $v^s_{y,w}$ is the average price per kilogram for species s during week w of (future year) y (assumed exogenous as the product is exported); $H^s_{y,w}$ is the harvest (kg) of prawns of species s during week w of year y (see Equation (7)); $E^f_{y,w}$ is the fishing effort targeted by fleet f (grooved or brown tiger prawns) during week w of year y; c_L, c_M is the share cost of labour and other variable costs per weight of output; c_K, c_F is the average repairs and maintenance, and fuel and grease costs per unit of effort; β_y is a discount factor (the rate at which future income or expenditures is discounted relative to the present value (Grafton *et al.* 2006)):

$$\beta = 1/(1+i)^{(y-y_{\text{cur}})} \tag{11}$$

i is the rate of interest, and y_{cur} is the current year.

The annual total cost is assumed to be the sum of labour, fuel (and grease) costs, depreciation, maintenance and repair costs, and other material costs. Labour costs are assumed to be proportional to revenue, while packaging and gear maintenance expenditures make up the bulk of the other items, the cost of which is proportional to the size of the catch in weight. Repair and maintenance costs and other costs (of which fuel is a major component) are assumed to depend on fishing effort.

The key choice variable in Equation (10) is fishing effort by fleet, week, and year. Fishing effort is selected to maximize Equation (10) over a 7-year projection period after which the effort corresponding to MEY (E_{MEY}) is reached. Thereafter, effort is kept at this level. The effort for the years prior to that in which the MEY target is achieved can thus be considered as 'transitional' effort.

5. Economic parameters

The values for the parameters of Equation (10) are estimated using data for 2006–2007 and for the first half of 2007–2008 (Kompas and Che 2008; AFMA 2008). The details of revenue, landings, and fishing costs are presented in Table 3. The ABARE survey data include 99 observations for 33 boats over three fishing seasons, and the tiger fishing season during the first half of 2007–2008, but the values for the parameters of Equation (10) are based on the most recent season and a half (last two columns in Table 3). All values in this dataset (including historical values) are real values at 2007–2008 prices. Relevant consumer and wholesale price indices are computed from the

Table 3 Summary statistics of the NPF (average per boat) for 2004/2005, 2005/2006, 2006/2007 and the first half of 2007/2008

Number of observed vessels	2004–2005	2005–2006	2006–2007	2007–2008(1)
	24	24	33	33
Part 1. Revenue and costs (average NPF vessel)				
Total revenue, including	$992 582	$1 061 117	$1 069 278	$547 800
Tiger revenue			$516 852	$424 935
Banana revenue			$490 264	$128 992
Endeavour revenue			$58 970	$45 231
Labour costs	$267 447	$263 950	$271 434	$126 720
Total materials costs	$49 035	$57 080	$73 358	$45 755
Fuel and grease costs	$296 786	$367 105	$293 493	$225 673
Repair costs	$142 368	$131 559	$126 774	$55 917
Gear costs	$34 706	$23 869	$19 265	$3972
Part 2. NPF Vessel summary (Average NPF vessel)				
Number of crews on board (persons)	3.2	3.5	4.3	4.3
Number of skippers (persons)			1.15	1.12
Total crew days (days)			832	487
Vessel size (m)	22	23	23.2	23.2
Vessel tonnage (tonnage)	148	170	167	122
Engine power (hpower)	346	363	349	333
Tiger prawn landed (kg)	21 998	23 547	24 580	21 963
Banana prawn landed (kg)	38 592	49 257	48 856	17 428
Endeavour prawn landed (kg)	3019	4680	4927	3492
Total prawn landed (kg)	65 801	79 264	78 772	43 280
Part 3. Economic parameters (Average NPF vessel)				
Share of labour per/$1 income ($)	$0.29	$0.26	$0.25	$0.23
Share of other cost/kg ($/kg)	$0.68	$0.67	$0.93	$1.06
Tiger fishing				
Repair cost ($/day)	$681	$802	$678.4	$483.8
Fuel cost ($/day)	$1440	$2251	$1570.6	$1952.6
Gear cost ($/day)	$167	$146	$103.10	$34.37
Banana fishing				
Repair cost ($/day)			$1356.87	$967.63
Fuel cost ($/day)			$3141.29	$3905.25
Gear cost ($/day)			$206.20	$68.74
Average price for tiger prawn ($/kg)	$17	$21	$21.03	$19.35
Average price for endeavours ($/kg)			$11.97	$12.95

Source: AFMA (2008), Kompas and Che (2008). Note: All values are in 2007–2008 prices.

data in AFMA 2008. The ABARE economic survey does not divide the NPF into the tiger prawn and the banana prawn fisheries. Therefore, average revenue and costs per vessel are computed from the NPF sample as a whole (see Table 3, part 1). The key vessel characteristics are also summarized for the whole fishery (see Table 3, part 2). The economic parameters for the tiger prawn fishery are estimated from the Kompas and Che (2008) economic survey dataset (see Table 3, part 3). Fuel and gear costs per unit of effort (c_F in Equation (10)) are estimated by dividing total fuel and gear costs by total fishing effort.

The bioeconomic model requires projections for the price of prawns and cost of fuel (the major variable cost component). Different projections are used in the sensitivity results, including constant price and cost assumptions, but forward projections for prices and the cost of fuel were constructed for a Base Case projection. The major driver of the price of prawns in the NPF is demand in Asian markets (especially Japan), which is largely dependent on the Yen-AUD exchange rate. The near-term exchange rate series is based on projections from ABARE (2007), and the relationship between exchange rates and the price of prawns is based on a forecast model of an otherwise standard ARIMA process (Kompas and Che 2008), where the main drivers are the exchange rate and projected increases in world prawn output (including aquaculture supplies in Asia). On this basis, the price of tiger prawns is expected to increase over the next 7 years by 12 per cent, due largely to a projected 'softening' of the Australian dollar from its current high values (for an indexed value of 100 in 2008, the subsequent annual prawn price indices are 102.1, 104.2, 106.8, 109.3, 111.6 and 112.0). The current price of tiger prawns in the NPF is \$19.35 per kg. Endeavour prawns (a relatively small component of total catch) are treated as an 'economic bycatch' in the model (affecting revenue and the cost of its catch (e.g. packaging) but not the cost of fishing related to effort).

Fuel prices for NPF vessels are net of a government 'fuel rebate' and currently stand at \$116.2 AUD per litre. Fuel prices in the NPF are assumed to follow a pattern similar to the Australian Farm Fuel Price index (see ABARE 2007), which is based on forecasts drawn from a number of sources, including time series data from Ampol, Caltex Australia, Fueltrac, and Shell Australia. The price of fuel is expected to fall slightly from its current high value (for an indexed value of 100 in 2008, the subsequent annual cost indices are 0.905, 0.888, 0.858, 0.836, 0.832 and 0.830). The discount rate, or rate of interest, in the Base Model projection is assumed to be 5 per cent.

6. Results

Equation (10) is maximized through a choice of annual effort subject to the constraints imposed by population dynamics model (Equations (1) to

(9)). Figures 1 and 2 show the estimated time trajectories for four key model outputs (the values prior to 2007 are from the stock assessment while those thereafter are projections based on the bioeconomic model) along with their bootstrap 90 per cent intervals. The vertical dashed lines in Figures 1 and 2 represent the fishing season just completed (year 2007). Both tiger species are assessed to have increased in recent years owing to the reduction in fishing effort (and hence fishing mortality), although unlike grooved tiger prawns, the spawning stock size for brown tiger prawns has not recovered to MSY by 2007 (Figures 1a,2a). Projections show that S_{MEY} should be obtained for grooved tiger prawns by 2010, and by 2013 for brown tiger prawns, in median terms (Figures 1b,2b). Effort increases over time as expected, with MEY

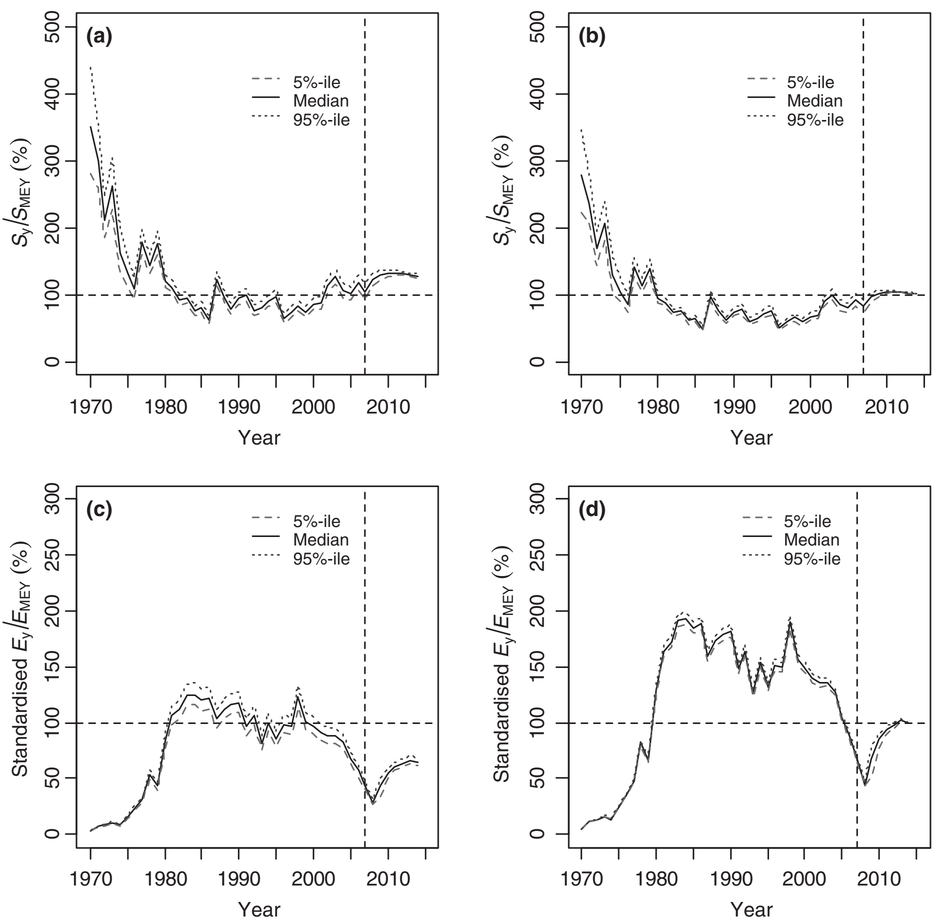

Figure 1 Median (with 5 and 95 percentiles) (a) spawning stock size in a year relative to the spawning stock size (S_{Y}) at Maximum Sustainable Yield (S_{MSY}), (b) spawning stock size in a year relative to that corresponding to Maximum Economic Yield (S_{MEY}), (c) standardized effort in a year (E_{Y}) relative to the effort at Maximum Sustainable Yield (E_{MSY}) and (d) standardized effort in a year (E_{Y}) relative to the effort at Maximum Economic Yield (E_{MEY}) for grooved tiger prawns for the Base Case projections.

being achieved by the end of the projection period (Figures 1d, 2d). The changes over time in effort do not reflect simply the impact of changes in stock size, but also those of the price of prawns, the cost of fuel and fishing efficiency (calibrated by fishing power estimates (see Bishop *et al.* 2008)). However, in the projections, fishing efficiency is assumed to remain at present levels.

Table 4 lists several summary statistics, including the ratio of the stock size at MEY to that at MSY is achieved (or S_{MEY}/S_{MSY}). Table 4 clearly indicates the presence of a 'stock effect'; the spawning stock at MEY is greater than that at MSY for both grooved and brown tiger prawns. For grooved tiger prawns S_{MEY}/S_{MSY} is 1.26 in the Base Case projection, and for brown tiger prawns it is 1.09. Results are comparable for the case when data from an independent fishery survey (conducted by a hired scientific vessel in the NPF) are used as the basis of the assessment instead of only on logbook data from industry (see the column 'Include Survey'). The 'stock effect' in the NPF corroborates results in Grafton *et al.* (2007), which showed a ratio of S_{MEY}/S_{MSY} greater than one for four species (yellowfin and bigeye tuna, tiger prawns and orange roughy) in the Pacific. Early bioeconomic modelling of tiger prawns in the NPF (Kompas and Che 2004) also showed the presence of a stock effect, albeit using a relatively simple Ricker equation to describe stock dynamics. The benefit of the current bioeconomic model, given by Equations (1) through (10), is that it fully integrates the economics with the current and ongoing stock assessment process used in the NPF. The last two columns in the table show the effect of no change in the price of prawns and the cost of fuel. As expected, constant prawn prices and no fall in the cost of fuel leads to a larger value for S_{MEY}/S_{MSY}. Recall that the Base Case assumes an increase in the price of prawns and a slight fall in the cost of fuel. At constant prices, MEY is achieved at a larger number of prawns than for the Base Case projection. In all cases, effort in 2007 is lower than effort at MEY

Table 4 Management targets (medians across the bootstrap replicates) for grooved and brown tiger prawns. Standardized Effort accounts for estimated increases in fishing power

	Base case	Include survey	No fuel change	No price change
Grooved tiger prawns				
S_{MEY}/S_{MSY}	1.264	1.260	1.309	1.307
S_{2007}/S_{MSY} (%)	105	117	105	105
S_{2007}/S_{MEY} (%)	83	93	80	80
Standardized E_{2007}/E_{MSY} (%)	43	43	43	43
Standardized E_{2007}/E_{MEY} (%)	67	67	73	73
Brown Tiger Prawns				
S_{MEY}/S_{MSY}	1.090	1.077	1.119	1.119
S_{2007}/S_{MSY} (%)	80	87	80	80
S_{2007}/S_{MEY} (%)	74	81	72	72
Standardized E_{2007}/E_{MSY} (%)	21	22	21	21
Standardized E_{2007}/E_{MEY} (%)	24	25	25	25

indicating a process of stock rebuilding and a transitional path to MEY with rising effort levels over time (Figures 1d,2d).

Sensitivity results are shown in Figures 3–5. Prices and costs matter greatly. Figures 3 and 4 show the effect on S_{MEY}/S_{MSY} of a change in the price of prawns and the cost of fuel. The point designated by '1' is the Base Case projection. Figure 3 shows the NPF should be 'fished harder', or at a stock size that approaches and eventually becomes lower than that at which MSY is achieved, as the price of prawns increases, although for S_{MEY} to be lower than S_{MSY} requires the current price of prawns to be at least three times higher than its current value. Figure 4 shows the effect of an increase in the cost of fuel. Again, the value '1' designates the Base Case projection. As

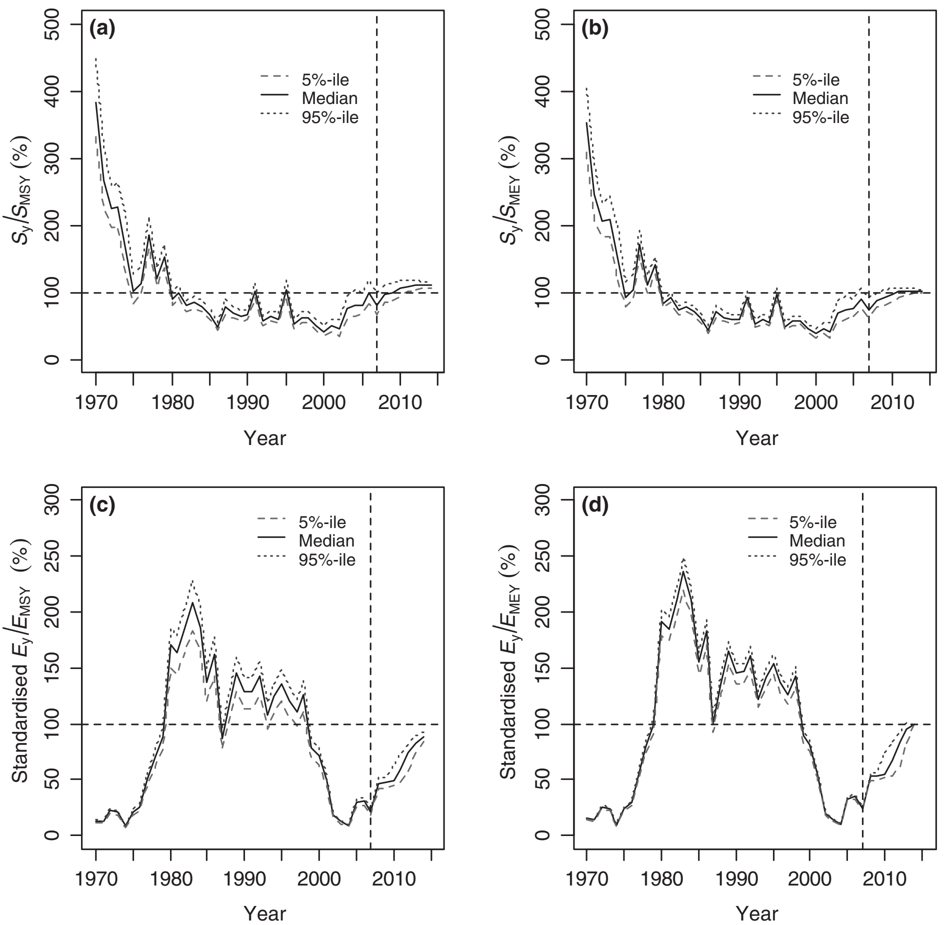

Figure 2 Median (with 5 and 95 percentiles) (a) spawning stock size in a year relative to the spawning stock size (S_Y) at Maximum Sustainable Yield (S_{MSY}), (b) spawning stock size in a year relative to that corresponding to Maximum Economic Yield (S_{MEY}), (c) standardized effort in a year (E_Y) relative to the effort at Maximum Sustainable Yield (E_{MSY}) and (d) standardized effort in a year (E_Y) relative to the effort at Maximum Economic Yield (E_{MEY}) for brown tiger prawns for the Base Case projections.

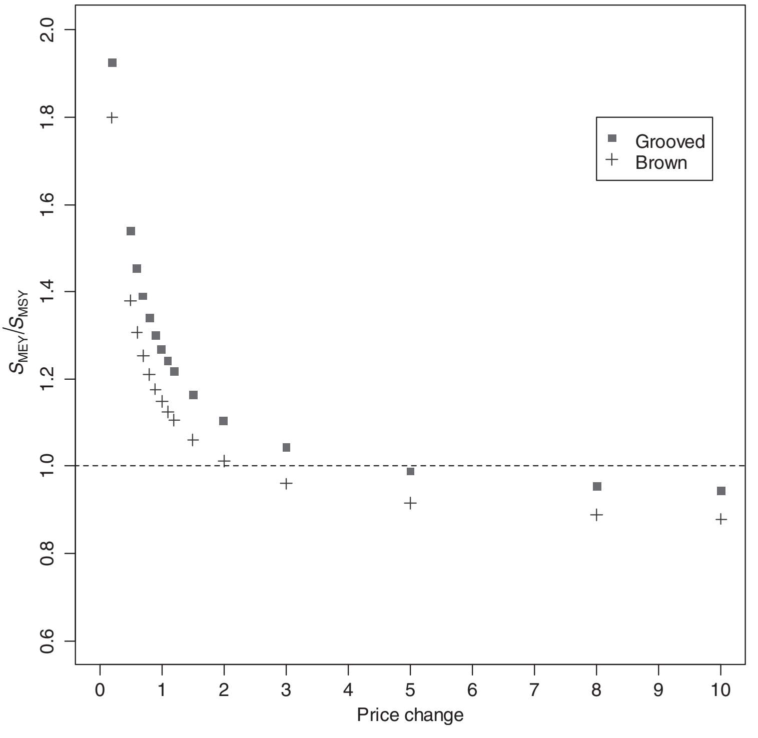

Figure 3 The effect of a change in the price of prawns (per kg) on $S_{\mathrm{MEY}}/S_{\mathrm{MSY}}$ for grooved and brown tiger prawns in the NPF. The value '1' corresponds to the Base Case projection. Each point on the *x*-axis represents a 100 per cent change in price of prawns.

expected, an increase in the cost of fuel results in a rapid increase in $S_{\mathrm{MEY}}/S_{\mathrm{MSY}}$. This is exactly what a 'stock effect' implies. It is profitable to have larger stocks of prawns so that the per-unit cost of harvest is smaller, or (alternatively) harvest per unit of effort is larger with increases in the cost of fuel. Finally, Figure 5 shows how insensitive $S_{\mathrm{MEY}}/S_{\mathrm{MSY}}$ is to the rate of interest or discount. $S_{\mathrm{MEY}}/S_{\mathrm{MSY}}$ does not reach unity until $i > 0.20$ for brown tiger prawns and > 1 for grooved tiger prawns. With substantial stock effects operating, the discount rate has a relatively minor impact.

7. Closing remarks

The NPF is one of the few fisheries in the world committed to an MEY target. In common with other examples in the Asia Pacific region (Grafton *et al.* 2007), MEY in the NPF occurs at stock sizes (for both grooved and brown tiger prawns) that are larger than that corresponding to MSY, implying a more 'conservationist' approach to fisheries management. Profits are maximized with 'thicker' stocks, thus decreasing the per-unit cost of fishing (or generating more catch at given effort levels). Model results detail both the target effort level and stock size, and the path to MEY, with standardized effort

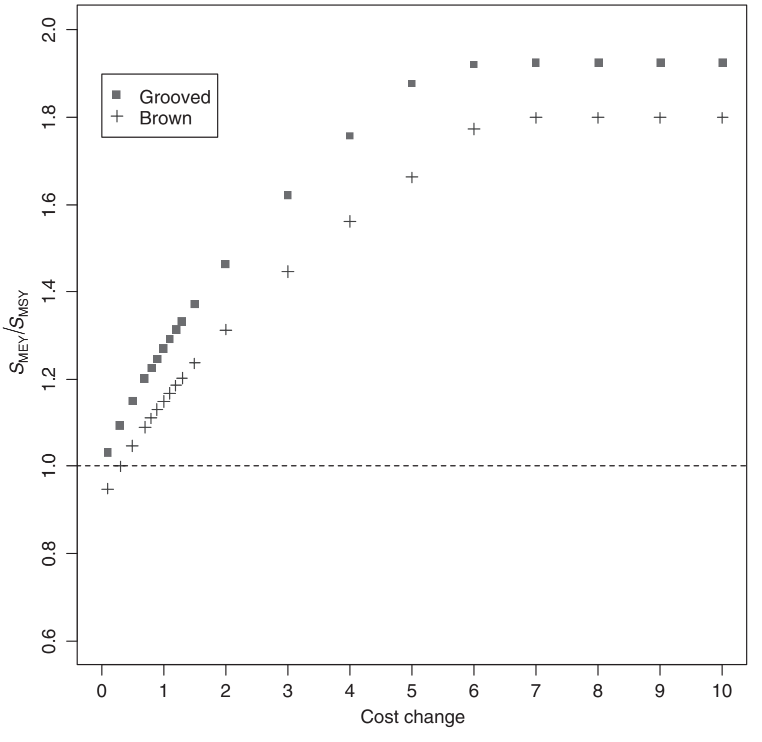

Figure 4 The effect of a change in the cost of fuel (per litre) on S_{MEY}/S_{MSY} for grooved and brown tiger prawns in the NPF. The value '1' corresponds to the Base Case projection. Each point on the x-axis represents a 100 per cent change in cost of fuel.

levels used as the 'real-time' fisheries management tool in the NPF. The MEY and the stock size at which it occurs varies given changes in prices and costs, as expected, but changes in the discount rate have little impact on the stock size corresponding to MEY given the presence of a substantial stock effect.

The model given by Equations (1) to (10) has now been used for the first time to set effort levels for the fishery for the 2008 and 2009 fishing seasons in the NPF. It was selected based on results from a management strategy evaluation exercise (Dichmont *et al*. 2008) which compared the performance of several alternative management strategies and showed that the bioeconomic model of this paper with a MEY-related target and a MSY-related limit reference point outperforms management strategies based on standard MSY-related target and limit reference points in terms of stock sustainability, short- and long-term profitability and effects on the habitat. The limit reference point would result in fishery closure if the average spawning stock size over the most recent 5 years is below half of the spawning stock at MSY.

The approach of this paper can be extended in several ways. For example, the model of the population dynamics could be modified to be, for example, age- or size-structured, or, more pertinently for the NPF, spatially structured. The economics model could be extended to take account of size-specific prices and/or cost information as well as vessel-class-specific costs. These types of

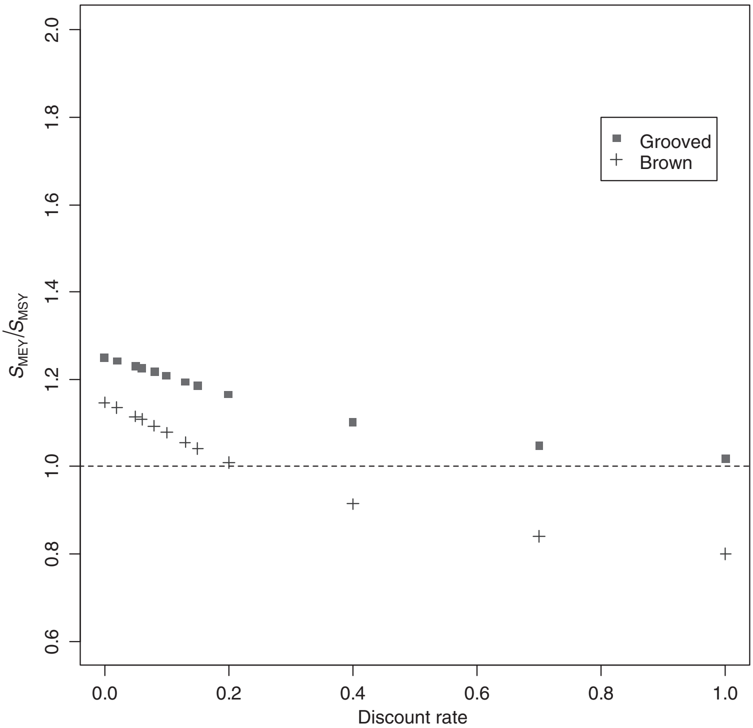

Figure 5 The effect of a change in the discount rate (rate of interest) on S_{MEY}/S_{MSY} for grooved and brown tiger prawns in the NPF. The discount rate in the Base Case projection is 0.05 or 5 per cent.

extensions have yet to be implemented for the NPF owing to lack of data to parameterize them.

However, there are some drawbacks to using the approach adopted for the NPF. The first is price uncertainty, particularly with regard to the cost of fuel. Any changes in fuel costs would imply the need to re-estimate MEY, although the MEY target will be larger than S_{MSY} at almost all reasonable values of the cost of fuel. This uncertainty is partly addressed in the NPF by the forecasting mechanism used to project fuel prices (Kompas and Che 2008), and partly by an updating process that requires re-evaluating MEY (as part of the ongoing stock assessment) every 2 years in a 'real-time' assessment of the fishery.

The second problem is more of a concern. Nothing in the model specifies fleet structure or the number of vessels needed to profitably obtain MEY. For MEY to literally hold, not only should catch or effort be at a level that guarantees the largest difference between the total revenue and costs of fishing, but the fishery must also employ the right amount of resources (including vessel capital), and in the correct proportions, to minimize the cost of harvest at MEY. At least one study, for banana prawns in the NPF (Kompas *et al.* 2004), shows this is unlikely to be the case. This has two implications. First, it is possible that some (and perhaps a good) part of fishery profits at MEY will be dissipated because of excess fishing capacity in the absence of a fisheries management instrument that ensures autonomous adjustment in the fleet. This may even be a necessary consequence with effort controls, although the assessment and management process in the NPF re-evaluates fishing power or potential effort creep every 2 years. Second, the current input control system may also result in changes in technical and allocative efficiency over time (Kompas *et al.* 2004), which are not currently accounted for in the model projections. This too can result in the dissipation of profits and incorrect measures of MEY. The NPF is currently considering a move to ITQs (and total catch controls) in large part to overcome these two concerns.

Finally, establishing MEY in a fishery when the current stock size is lower than S_{MEY} requires a process of stock rebuilding, and the NPF, partly on the basis of the current MEY target, is currently undergoing rebuilding, with substantial cuts in effort to achieve MSY (the target prior to MEY), also occurring in recent years. Once MEY has been obtained profits will be maximized, but the path to MEY thus necessarily requires substantial cuts in harvest and revenues. This can be a problem. Although optimality implies that the gains at MEY will more than compensate for the losses in transition, the transition can be burdensome on a fishing industry that is interested manly in 'cash flow' and short-term returns. Economic losses are also often distributed unequally across vessels in transition. This point alone makes implementing MEY in other fisheries often difficult to accomplish, especially those in which current stock size in much lower than S_{MEY}. Fortunately, the NPF has benefited by a recent structural adjustment package in terms of a voluntary government-funded buyout that removed over 40 vessels from the fishery (reducing the fleet by almost half). This has not only helped ease the transition to MEY, but may have also generated a more appropriate fleet size and structure, assuming that less efficient vessels opted to leave the fishery in the buyout. At the least, the current MEY target will guarantee that profits are maximized regardless of changes in prices and costs, over every two-year projection in the 'real-time' assessment, as well as ensuring that fish stocks are relatively protected at values greater than stocks at MSY.

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