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Optimal vessel size and output in the Australian northern prawn fishery: a restricted profit function approach*

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Individual transferable quotas (ITQs) are to be introduced into Australia's Northern Prawn fishery in the near future. Total allowable catches (TACs) are to be set with the objective of maximising economic efficiency in the fishery. Under ITQs, vessel owners have the ability to adjust their fishing activities to maximise profits and changes in fleet structure resulting from management changes need to be considered when determining TACs. A restricted profit function for the fishery was estimated to determine the optimal vessel characteristics and output levels as a guide to how the fleet may adjust under an ITQ system. Vessels were found to be currently close to their optimal size given average historic prices and current stock conditions. However, higher tiger prawn stocks are expected to result in the average size of vessels increasing, with rising fuel prices also likely to result in capital being substituted for fishing days. Optimal average vessel-level catches of the main species are lower than current average vessel catches for a wide range of input and output prices. These changes in vessel characteristics and behaviour need to be incorporated in the derivation of the optimal TACs if economic efficiency objectives are to be achieved.

Key words: fuel prices, individual transferable quotas, optimal vessel size, profit function.

1. Introduction

The introduction of individual transferable quotas (ITQs) in the Australian Northern Prawn Fishery (NPF) in 2012 will provide a greater incentive for vessel owners to adjust their input use and scale of operation in the light of changing economic conditions. Fishers will have an incentive to adjust their

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input and output mix to either minimise costs for a given level of output (as determined by their quota allocation) or alter both their input and output levels to maximise profits. Determining how fishers will adjust their input and output mix requires an understanding of the cost structures facing the industry, and also the impact of changing prices on vessel profits. Dual approaches, such as cost and profit functions, are appropriate to analyse fisher behaviour and performance in the light of changing management conditions (Jensen 2002).

The need to determine how fleets may respond to the changing management-induced incentives is even greater for the NPF, as the fishery has an explicit goal of achieving maximum economic yield (MEY) – the first large commercial fishery in the world to do so. Total allowable catches (TACs) for the main species are to be set using a bioeconomic model of the fishery (Dichmont *et al.* 2008, 2010). Incorporating expectations of changes in cost structures into the analysis is essential if appropriate TACs are to be set and the objective of MEY to be achieved.

In this paper, a restricted profit function is estimated for the NPF using economic data collected from individual fishers since the early 1990s. The model is used to derive estimates of the individual vessel size and output level that maximise individual vessel profits given different input and output price levels.

The remainder of the paper is organised as follows. First, a brief description of the fishery is provided. Then, a description of the methods used is presented, followed by a description of the economic data. Next, the empirical results are presented, followed by a discussion and conclusions.

2. The northern prawn fishery

The NPF is one of Australia's most valuable fisheries in terms of total landed value. In 2007–2008, the gross value of product was estimated to be around \$74m (ABARE 2009), although in previous years it had been in excess of \$150m (Newton *et al.* 2007). In more recent years, profitability in the fishery has been adversely affected by falling prawn prices (Figure 1) and rising fuel prices (Figure 2). Declining prawn prices have largely been caused by a combination of increased aquaculture supply of prawn on the world market and, in the last few years, a strengthening of the Australian Dollar against the currencies of major importers of Australian prawns, especially the US Dollar and Japanese Yen (Wood *et al.* 2008). The increase in fuel prices has resulted in fuel costs increasing from 15 per cent of total costs in 1994–1995 to almost 40 per cent in 2005–2006 (Brown 1997; Vieira and Hohnen 2007) (Figure 2).

The fishery occurs over two 'seasons' each year, which can also effectively be considered as two separate subfisheries – namely a 'banana prawn fishery' and a 'tiger prawn fishery'. The banana prawn fishery occurs during the first season, which generally runs from March/April to June. White banana prawns (*Fenneropenaeus merguiensis*) caught in the Gulf of Carpentaria

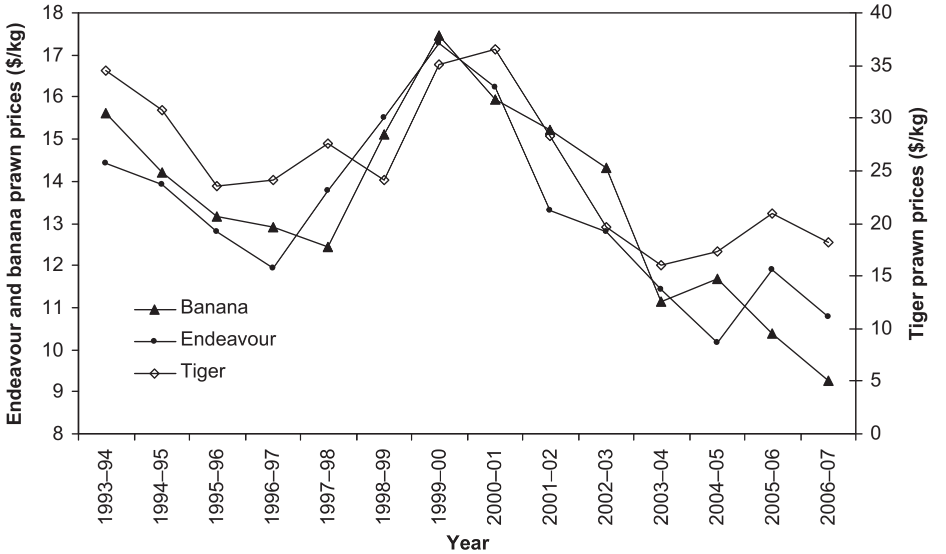

Figure 1 Real prices of the main species caught in the northern prawn fishery (2006 prices).

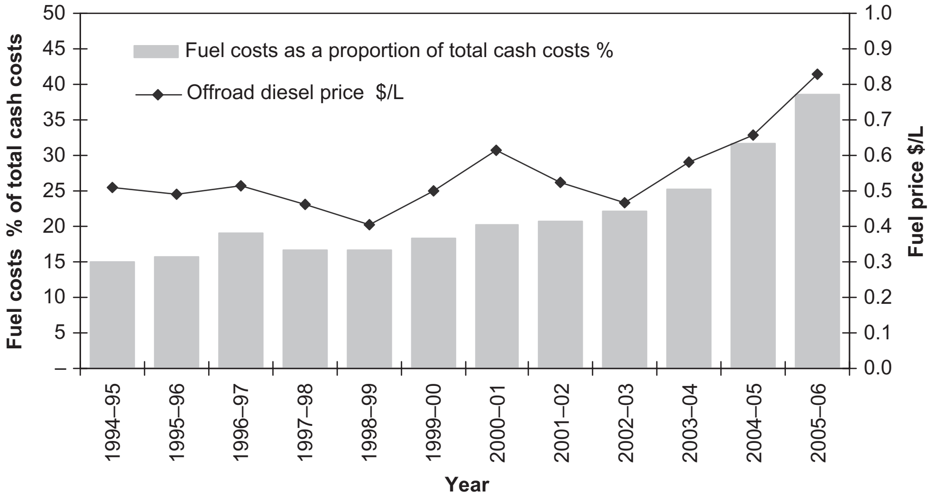

Figure 2 Fuel cost shares and real off-road diesel price, northern prawn fishery (2005–2006 prices).

dominate the total catch during the first season, when these prawns form dense spawning aggregations. As a consequence, large quantities of *F. merguiensis* can be caught over the relatively short season (Die and Ellis 1999), and the fishery has historically been characterised by a race to fish.

The tiger prawn fishery occurs during the second season, which generally runs from August/September to October/November/December. The key species caught during the second season are brown tiger prawns (*Penaeus esculentus*), grooved tiger prawns (*P. semisulcatus*) and two endeavour prawn species (*Metapenaeus endeavouri* and *M. ensis*). These species are generally more dispersed relative to *F. merguiensis* so different fishing gears and behaviours are consequently employed. Catches of these species are predominantly taken in the Gulf of Carpentaria. A number of other prawn species (e.g. red-legged banana prawns, king prawns) as well as fish, cephalopods and other crustaceans are also caught as by-products during both seasons.

The fishery is rather unique – both in Australia and internationally – as it has an explicit management objective of maximising the economic returns from the fishery (Dichmont *et al.* 2010). The fishery is currently managed using a combination of input controls, primarily seasonal closures and individual transferable gear units. Effort levels in the tiger prawn fishery are set using a bioeconomic model that optimises economic returns in the fishery over time rather than on a year-by-year basis (Dichmont *et al.* 2008). Over the last decade, the fleet size has more than halved, from 133 vessels in 1998 to 52 in 2008, largely as a result of management action resulting in an industry-funded buyback in 2001 (which removed 36 vessels), and a government-funded vessel buyback in 2006 (which removed 43 vessels) and consolidation of gear units (DAFF 2006; Larcombe 2008). More recently, the decision has been made to change the management system in the fishery to ITQs, with these to be implemented in 2012.

3. Methodology

The key objective of the study was to estimate the average optimal vessel size and catch, taking into consideration expected changes in prices and stock conditions. The move to ITQs in the fishery will provide incentives for fishers to adjust their activity levels in response to these conditions, and any estimation of future TACs will need to take into account the expected future cost structure of the industry as well as expected changes in input and output prices. An advantage of using a profit function to estimate the optimal size and activity levels is that it allows for variation in both inputs and outputs, with both assumed to be endogenous with respect to their relative prices.

Following Squires (1987) and Andersen *et al.* (2008), the most general form of the restricted profit function is given as $\mathrm{HR}(p,z)$, where HR is the short-term restricted profit defined as total revenue less the variable costs, p is a vector of variable input and output prices, and z is a vector of quasi-fixed inputs. The function is restricted because it depends on the existing level of quasi-fixed inputs. Total profits can be given by $\mathrm{HT}(p,p_z,z) = \mathrm{HR}(p,z) - p_z,z$, where p_z is a vector of the (market) user prices of the quasi-fixed inputs. From Hotelling's lemma (Hotelling 1932), $\delta\mathrm{HR}(p,z)/\delta p = Q(p,z)$ and $\delta\mathrm{HR}(p,z)/\delta z = -p_z^*$, where $Q(p,z)$ is the profit maximising level of outputs or inputs given the set of prices and the level of quasi-fixed factors, and p_z^* is the shadow prices of the quasi-fixed factors. The optimal level of the quasi-fixed factors is determined by equating the shadow price to the service price, such that $\delta \mathrm{HR}/\delta z = p_z$ (Squires 1987). Given this, the optimal equilibrium level of inputs and outputs (i.e. after quasi-fixed factors have been optimised) is given by $\delta \mathrm{HR}(p,z^*(p,p_z))/\delta p$, where $z^*(p,p_z)$ is the long-run equilibrium level of the quasi-fixed factors given the set of prices. Although restricted profit functions have been estimated for a wide range of industries, relatively few attempts to estimate profit functions have been made in fisheries (Squires 1987, 1988; Asche *et al*. 2007; Andersen *et al*. 2008). This is most likely due to a lack of an appropriate time series of economic information in most fisheries.

A range of functional forms of the profit function are available, the most frequently used being the translog. This is a relatively flexible functional form, because it does not impose assumptions about constant price elasticities nor elasticities of substitution between inputs and outputs. The generic form of the translog profit function is given by

$$\begin{aligned}\ln \mathrm{HR} = {} & \alpha_0 + \sum_i \alpha_i \ln P_i + \frac{1}{2}\sum_{i \neq j}\sum_{j \neq i} \alpha_{ij} \ln P_i \ln P_j + \sum_i \alpha_{ii} \ln^2 P_i \\ & + \sum_k \beta_k \ln Z_k + \sum_{k \neq l}\sum_{l \neq k} \beta_{kl} \ln Z_k \ln Z_l + \sum_k \beta_{kk} \ln^2 Z_k \\ & + \sum_i \sum_k \beta_{ik} \ln P_i \ln Z_k + \gamma t + \gamma_{tt} t^2 + \sum_i \gamma_i \ln P_i t + \sum_k \gamma_k \ln Z_k t, \quad (1)\end{aligned}$$

where HR is the observed level of short-run profit, P_i and P_j are the prices of the variable inputs and outputs i and j; Z_k and Z_l are the quasi-fixed input quantities k and l, and t is a time trend used to estimate the effects of technical progress.

The restricted profit function was normalised by the price of one of the outputs (P_1), with the functional form of the estimated model given by

$$\begin{aligned}\ln(\mathrm{HR}/P_1) = {} & \alpha_0 + \sum_{i>1} \alpha_i \ln(P_i/P_1) + \sum_{i \neq j \neq 1}\sum_{j \neq i \neq 1} \alpha_{ij} \ln(P_i/P_1) \ln(P_j/P_1) \\ & + \sum_{i>1} \alpha_{ii} \ln^2(P_i/P_1) + \sum_k \beta_k \ln Z_k + \sum_{k \neq l}\sum_{l \neq k} \beta_{kl} \ln Z_k \ln Z_l \\ & + \sum_k \beta_{kk} \ln^2 Z_k + \sum_{i>1}\sum_k \beta_{ik} \ln(P_i/P_1) \ln Z_k \\ & + \gamma_t t + \gamma_{tt} t^2 + \sum_{i>1} \gamma_i \ln(P_i/P_1) t + \sum_k \gamma_k \ln Z_k t. \quad (2)\end{aligned}$$

Homogeneity in input and output prices requires $\sum_i \alpha_i = 1$, $\sum_i \alpha_{ij} = 0$, $\sum_i \beta_{ik} = 0$ and $\sum_i \gamma_i = 0$, while symmetry in input and output prices requires

$\alpha_{ij} = \alpha_{ji}$. Hence, the parameters of the output used in the normalisation can be derived using the homogeneity conditions (e.g. $\alpha_1 = 1 - \sum_{i>1} \alpha_i$).

From Hotelling's lemma, the partial derivative of the profit function with respect to the input and output prices ($\ln P_i$) yields a set of profit share equations, given by

$$S_i = \alpha_i + 2\alpha_{ii} \ln P_i + \sum_{j \neq i} \alpha_{ij} \ln P_j + \sum_k \beta_{ik} \ln Z_k + \gamma_i t \tag{3}$$

where $S_i = P_i Q_i/\mathrm{HR} = (P_i/P_1)Q_i/(\mathrm{HR}/P_1)$ is the profit share of the ith input or output, and Q_i is the quantity of the input/output used or produced. These share equations also represent the input demand and output supply equations.

The profit function in Equation (2) and the associated set of share equations given by Equation (3) need to be estimated simultaneously. The system of equations is estimated using Zellner's seemingly unrelated regression (Zellner 1962). Restrictions are imposed across the system to ensure that the estimated coefficients in each equation are equivalent (i.e. that the α_i coefficients estimated in the share equations take the same value as the α_i coefficients in the profit function).

The partial static equilibrium own- and cross-price elasticity of input demand or output supply can be derived from the share equations, given by

$$\eta_i = (\alpha_{ii} + S_i^2 - S_i)/S_i, \;\; \eta_{ij} = (\alpha_{ij} + S_i S_j)/S_i. \tag{4}$$

These short-run elasticities are only valid at the given level of quasi-fixed factors and exclude the effects of changes in these factors in response to the set of prices. In contrast, long-term elasticities including both expansion and substitution effects can be given by

$$\varepsilon_{ii} = (\alpha_{ii} + S_i^2 - S_i)/S_i - (\beta_{iz} + S_i S_z)^2 \Big/ S_i\big(\beta_{zz} + S_z^2 - S_z\big) \tag{5}$$

$$\varepsilon_{ij} = (\alpha_{ij} + S_i S_j)/S_i - (\beta_{iz} + S_i S_z)\big(\beta_{jz} + S_j S_z\big)/S_i\big(\beta_{zz} + S_z^2 - S_z\big) \tag{6}$$

$$\varepsilon_{zz} = S_z/(\beta_{zz} + S_z^2 - S_z) \tag{7}$$

$$\varepsilon_{iz} = S_z(\beta_{iz} + S_i S_z)/S_i(\beta_{zz} + S_z^2 - S_z) \tag{8}$$

$$\varepsilon_{zi} = (\beta_{iz} + S_i S_z)/(\beta_{zz} + S_z^2 - S_z) \tag{9}$$

where $S_z = -p_z z/\mathrm{HR}$ (Squires 1987; Andersen *et al.* 2008). All long-run elasticities are evaluated at the optimal levels z*.

4. Data

Annual cost and earnings data for the fishery are collected by the Australian Bureau of Agricultural and Resource Economics (ABARE). Information on catch, effort and vessel characteristics is collected through a logbook program run by the Australian Fisheries Management Authority (AFMA). The data set considered for the model was limited to the period 1994–1995 to 2005–2006. Although earlier data were available, these were not included in the modelling because the industry went through a substantial restructuring in 1993–1994. Economic data after 2005–2006 were not available at the time of the analysis.

The industry again went through a substantial restructuring during 2005 and 2006. The data set was limited to only those vessels that remained in the fishery in 2007 because the aim of the analysis was to estimate how the fleet may change from its current structure. The remaining vessels were, on average, 15 per cent larger than those that left the fishery in terms of engine power (although this difference was not statistically significant at the 5 per cent level), and had, on average, 26 per cent higher catches of banana prawns (again, not statistically significant at the 5 per cent level). Average headrope length and catches of other prawn species for the remaining boats were almost identical to those that left the fishery.

The final data set contained 265 observations over the 12-year period and included 29 of the remaining 52 boats in the fishery. The panel data set was unbalanced as vessels entered the economic survey at different points in time, although at least 10 continuous years of data were available for the majority of boats.

The exact average prices paid to vessels for their catch was not known, as this is affected by the size composition of the catch. However, information was available on average prices of the different species (Figure 1), the total catch of each species (in kg) and the total revenue of the vessels (across all species). Annual vessel-level prices were estimated by scaling up (or down) the average price by the ratio of the estimated total revenue from the product of the logbook catch and average price data to the total revenue reported in the annual economic survey. The assumption underlying this is that differences in price reflect vessel specificity in the size compositions of the catch. A necessary implicit assumption also was that the prices could be adjusted by the same proportion for all species. In all cases, the adjusted prices were within the observed size-related price range of the various prawn species. All prices were inflated to their 2005–2006 equivalent real value using the Australian consumer price index.

As prices of the main species were highly correlated ($r > 0.8$), the species were aggregated into two groups reflecting the seasonal differences in catch – banana prawns and a tiger prawn group, which included both species of tiger prawns and endeavour prawns. The two tiger prawn species are not marketed separately so share an identical price. Endeavour prawns are primarily a bycatch species. The average price for the group at the vessel level was determined by the total estimated revenue (derived from the catch of each species by the vessel multiplied by its estimated vessel-specific price) divided by the sum of the vessel's catches of these species.

As in many fisheries, crew are generally paid a share of the revenue. That is, there is no explicit price for labour, and crew payments are directly related to catches and prawn prices, not profit. The effective price received by the owner is the prawn price less the share paid to the crew, so prawn prices were adjusted to a price net of crew share. Similarly, freight- and marketing-related costs are based on a $/kg basis, which could be derived from the economic survey and logbook catch information for each vessel and for each year. This was also deducted from the prawn price. An implicit assumption in the analysis is that investment and production decisions are made not on the market price *per se*, but on the effective price received by the vessel owner after crew and marketing deductions.[1]

Other information included in the analyses was derived from logbook and vessel registry databases. This included boat engine power and the length of headrope used by the vessel when trawling. The combination of these variables influences the area swept by the vessel per unit of time. Finally, annual stock indexes were incorporated into the profit function as nondiscretionary inputs. For the tiger and endeavour prawns, the stock indexes were derived from exploitable biomass estimates derived from stock assessments (Dichmont *et al.* 2003; Deng *et al.* 2008). A composite stock index incorporating both the tiger and endeavour species was derived from the individual species' stock index weighted by their revenue shares. No stock assessment is undertaken for banana prawns, so an index of relative stock abundance for this component of the catch was estimated based on the average catch per (effective) hour in the first week of the season.[2] The length of both the banana and tiger season (in days) was included as explanatory variables as these potentially constrain individual vessels' catches.

As the data were panel data, dummy variables for each boat were also included in the analysis to capture any fixed vessel effects. These fixed effects are related to a measure of the relative efficiency of the different vessels.

[1] A reviewer suggested an alternative approach would be to either include an opportunity cost measure for labour (Clark and Munro 1980; Squires 1987, 1988) or to treat crew payments as part of short-term profit. This would have enabled estimation of an optimal vessel size and output from a broader societal perspective, but production decisions in the fishery are made by the vessel owner based on their returns on their investment. Hence, optimality conditions in a fishery operating under a share system are defined in terms of the share-weighted index of input and output prices rather than observed market prices (McConnell and Price 2006).

[2] Catch rates are not a perfect indicator of abundance given that fishing for banana prawns takes place on spawning aggregations. Catch rate decreases over the fishing season as the stock is depleted and is influenced by both the remaining available resource and also the level of effort expended in previous periods, which in turn is influenced by prawn and fuel prices. The catch rate in the first week is predominantly influenced by availability rather than previous effort levels. Further details on the use of catch rates as a proxy for the stock index is given in the Data S1.

A summary of the data used in the analysis is given in Table 1. For the analysis, all variables were normalised by dividing through by their mean value. Consequently, the normalised variables had a mean value of 1, and a logged mean value of zero. Prices were further normalised by the banana prawn price to ensure homogeneity. The estimated equations, then, only explicitly include tiger prawn and fuel prices, headrope length, engine power, season length (for each season), stock indexes for both banana and tiger prawns, a time variable and vessel dummy variables. Because the restricted share equations sum to unity, one must be excluded from the analysis. In this case, the fuel share equation was not explicitly estimated, but the parameters relevant to fuel supply can be derived from the profit function. The parameters relevant to the banana prawn output are derived from the homogeneity conditions. Hence, *ex ante* homogeneity expectations are realised *ex post* (Squires 1987).

5. Results

Several variants of the model were tested. Initial analysis indicated that the season length and time variables were correlated, and a complete model with season and time interactions with the other variables could not be estimated because of singularity problems. The models were estimated with different combinations of season and time interactions. The best model, based on the Akaike Information Criterion, excluded the interaction terms between the two season variables and also the time variables with the other explanatory variables (Table 2).

The estimated coefficients of the final restricted profit function are presented in Table 3, along with some basic goodness-of-fit statistics. The coefficients relating to banana prawn price were derived from the base model using the homogeneity conditions and are also included in Table 3. The coefficients for the share equations are embedded in the profit function so are not repeated separately. The estimated restricted profit function explained around two-thirds of the observed variability in vessel profits, while the share equation had a lower R^2 value. While these R^2 values may appear low, they are consistent with those for other estimated profit functions (Asche *et al.* 2007). More importantly, the coefficients generally have the expected sign and many are significant at the 10 per cent level or greater.[3]

[3] The potential for heteroscedasticity was tested using White's general heteroscedasticity test (White 1980), and no problems were identified ($\chi^2_{31DF} = 0.03$). The software used (SHAZAM) was unable to provide a specific test for panel data autocorrelation when a system of equations was estimated. However, the nonparametric run tests suggested that no autocorrelation existed in the main profit function ($R = 134$, $u^+ = 150$, $u^- = 115$, $E(R) = 131.2$, $\sigma_R = 7.98$, $\Pr(0 \leq Z \leq (E(R)-R)/\sigma_R) = 0.36$), but some positive autocorrelation may exist in the share equation ($R = 108$, $u^+ = 124$, $u^- = 141$, $E(R) = 132.9$, $\sigma_R = 8.09$, $\Pr(0 \leq Z \leq (E(R)-R)/\sigma_R) = 0.99$). This may result in some of the standard errors for the variables in this model being underestimated. However, the parameter estimates themselves remain unbiased as well as consistent and asymptotically normally distributed.

Table 1 Summary of key data† used in the analysis (2005–2006 prices)

	Mean	SD	Minimum	Maximum
Restricted profit ($'000/boat)	801.9	349.3	68.8	1737.6
Banana price ($/kg)‡	11.1	2.5	6.7	21.1
Tiger price ($/kg)‡§	17.9	4.6	10.7	34.1
Fuel price (c/L)	53.4	10.1	40.3	82.9
Headrope length (m)	13.2	1.4	7.8	16.0
Engine power (kW)	388.3	43.4	261.0	450.0
Banana stock index	1.093	0.373	0.474	1.877
Tiger stock index	1.166	0.150	0.850	1.555
Banana season (days)	57.9	13.2	42.0	74.0
Tiger season (days)	106.8	12.8	91.0	121.0
Share tiger revenue	0.67	0.38	0.00	4.83
Share banana revenue	0.70	0.30	0.04	2.66
Share fuel costs	−0.37	0.45	−6.49	−0.11

†Source: Profit and price data derived from ABARE surveys of the fishery (e.g.); vessel data (including catch and effort data) derived from data provided by Australian Fisheries Management Authority; Tiger prawn stock data derived from CSIRO modelling of the fishery (e.g.).
‡Net of crew share (% of revenue) and freight costs ($/kg).
§Tiger price is a weighted average of tiger and endeavour prawn prices.

Table 2 AIC for different model specifications varying time and season interactions

		Season length		
		$\varsigma, \varsigma_{ss}, \varsigma_i, \varsigma_k \neq 0$	$\varsigma_i, \varsigma_k = 0$	$\varsigma, \varsigma_{ss}, \varsigma_i, \varsigma_k = 0$
Time	$\gamma, \gamma_{tt}, \gamma_i, \gamma_k \neq 0$	na	71.62	89.09
	$\gamma_i, \gamma_k = 0$	70.60	63.26	83.95
	$\gamma, \gamma_{tt}, \gamma_i, \gamma_k = 0$	78.98	88.80	103.95

Note: $\gamma, \gamma_{tt}, \gamma_i, \gamma_k$ are the parameters relating to time and its interactions with prices and other variables (including season); $\varsigma, \varsigma_{ss}, \varsigma_i, \varsigma_k$ are the parameters relating to the two seasons and their interactions with prices and other variables (including time).

The squared term coefficient relating to technical change in the revised model was significant and negative, suggesting that profitability declined over time, ceteris paribus. Technical change appeared to be unrelated to vessel characteristics, suggesting that these changes arose from external factors (i.e. disembodied technical change). Technical change in this context is change in individual vessel profitability not explained by price changes or vessel characteristics. The fishery was subject to numerous restrictions over the period of the analysis that may have accounted for this apparent decline, including potential transitional difficulties in the introduction of gear units in 2000 and the subsequent restrictions on headrope length, the introduction of turtle excluder devices and bycatch reduction devices (believed to have initially reduced productivity by around 6 per cent (Brewer *et al.* 2006)), and the change in the opening date of the second season from 1 August to 1 September in 2002–2003 to 2004–2005. This latter change was implemented with the explicit aim to reduce catches of one of the tiger prawn species. The season

Table 3 Parameter estimates of the restricted profit function

	Coefficient	t-statistic		Coefficient	t-statistic
Constant	1.376	6.445***	Vessel dummies		
Tiger prawn price	0.674	33.590***	D2	−0.043	−0.625
Banana prawn price	0.372	4.883***	D3	−0.455	−5.496***
Fuel price	−0.045	−0.611	D4	−0.522	−6.436***
Tiger stock index	0.883	4.429***	D5	−0.438	−5.809***
Banana stock index	0.086	1.263	D6	−0.428	−5.133***
Headrope length	0.527	1.752*	D7	−0.434	−4.961***
Engine power (kW)	0.712	2.751***	D8	−0.259	−3.076***
Banana season length	−0.752	−2.612***	D9	−0.443	−5.155***
Tiger season length	−0.384	−0.830	D10	−0.441	−5.035***
Tiger price^2	0.260	3.127***	D11	−0.378	−4.068***
Banana price^2	0.705	3.722***	D12	−0.354	−4.318***
Fuel price^2	0.107	0.770	D13	−0.313	−3.546***
Tiger stock index^2	−0.479	−0.476	D14	−0.300	−3.558***
Banana stock index^2	−1.304	−3.168***	D15	−0.547	−5.884***
Banana season^2	2.009	2.891***	D16	−0.507	−5.412***
Tiger season^2	−39.050	−5.075***	D17	−0.342	−3.766***
Headrope^2	0.566	0.572	D18	−0.586	−6.217***
Engine power (kW)^2	−3.858	−3.193***	D19	−0.445	−3.779***
Tiger price × fuel price	0.169	2.161**	D20	−0.354	−3.915***
Tiger price × banana price	−0.429	−4.928***	D21	−0.458	−5.478***
Tiger price × tiger stock	0.116	0.479	D22	−0.269	−2.546**
Tiger price × banana stock	−0.323	−4.846***	D23	−0.263	−2.236**
Tiger price × headrope	−0.583	−2.545**	D24	−0.421	−4.377***
Tiger price × engine power	0.130	0.785	D25	−0.533	−5.361***
Banana price × fuel price	−0.276	−1.803*	D26	−0.459	−3.859***
Banana price × tiger stock	−0.476	−0.896	D27	−0.482	−4.658***
Banana price × banana stock	0.296	1.305	D28	−0.297	−2.850***
Banana price × headrope	−0.364	−0.507	D29	−0.187	−1.770*
Banana price × engine power	−0.649	−1.557			
Fuel price × tiger stock	0.360	0.732			
Fuel price × banana stock	0.027	0.123			
Fuel price × headrope	0.947	1.354			
Fuel price × engine power	0.519	1.319	R^2		
Tiger stock × headrope	−1.472	−0.997	System		0.6734
Banana stock × headrope	−1.836	−2.496**	Profit function		0.6734
Tiger stock × engine power	2.748	3.030***	Tiger prawn share		0.2255
Banana stock × engine power	0.538	1.341			
Tiger stock × banana stock	−1.854	−2.803***	Raw moment R^2		
Headrope × engine power	2.276	1.640	Profit function		0.6734
Time	0.047	1.308	Tiger prawn share		0.8169
Time^2	−0.011	−3.585***			

***Significant at the 1% level; **significant at the 5% level; *significant at the 10% level.

was extended at the other end by 3 weeks, but the timing of the season has a different impact to its length.

The coefficients on season length were also generally negative, suggesting that average profits decreased with increasing season length. Given that most boats are operated by employed skippers and crew who are paid on the basis of catch (not profit), it is unsurprising that fishing activity continues beyond the point where falling catch rates, and subsequently marginal revenues, are less than the marginal cost of fishing.

The coefficients relating to the stock indices were positive, as expected, with a tiger prawn stock elasticity of 0.88, suggesting that profitability is closely related to the health of the tiger prawn stock. In contrast, the estimated banana prawn stock elasticity was small (0.08) and nonsignificant. Given the race to fish that occurs in the banana prawn fishery, high stocks may not necessarily lead to proportionally high profit levels, although this effect may change when ITQs are introduced into the fishery. It may also, however, be an artefact of a stock index that may not adequately capture changes in stock abundance. Relatively high profits were observed in the fishery in 2007–2008 and 2008–2009 – both years with a high banana prawn stock, but also following the large fleet reduction (Vieira *et al.* 2010).

The vessel dummy variables were generally significant and all negative. The base vessel was chosen on the basis that it was one of four vessels for which data were available for all years, and by coincidence appears to be the most efficient vessel. The relative economic efficiency of the vessels can be derived assuming the base vessel has an efficiency score of 1. Most vessels were operating at between 60 and 70 per cent efficiency (Figure 3). These efficiency scores are lower than technical efficiency scores previously estimated for the banana (Kompas *et al.* 2004) and tiger prawn (Pascoe *et al.* 2010) fisheries separately. The profit efficiency measure is a combination of both technical and allocative efficiency, as both quantity of catch and input use is taken into consideration, given the set of relative prices. This suggests that while vessels are largely technically efficient (i.e. taking the greatest catch for a given input level), an economically more efficient catch may have resulted through varying the input and/or output mix.[4]

5.1. Short- and long-run price elasticities

Derivation of short- and long-run input demand and output supply price elasticities requires an estimate of the optimal level of the quasi-fixed inputs. As noted previously, the long-run equilibrium level of the quasi-fixed factors (engine power and headrope length) is given by $\delta \mathrm{HR}(p,z^*(p,p_z))/\delta p = p_z$, where p_z is the real capital service price. As all prices have been normalised, then the appropriate 'average' user price is 1. An analytical solution is not possible, requiring a numerical solution (Squires 1987). The optimal engine power and headrope length were estimated at varying fuel and prawn price combinations using a nonlinear programming model developed in GAMS (Brooke *et al.* 1996). Several starting values were used to ensure that the

[4] The race to fish in the banana prawn component of the fishery is one such example where too many inputs may be employed to take the catch at its most profitable level. The subsequent results on the optimal vessel size and catches also demonstrate the imbalance between current and optimal input use and output.

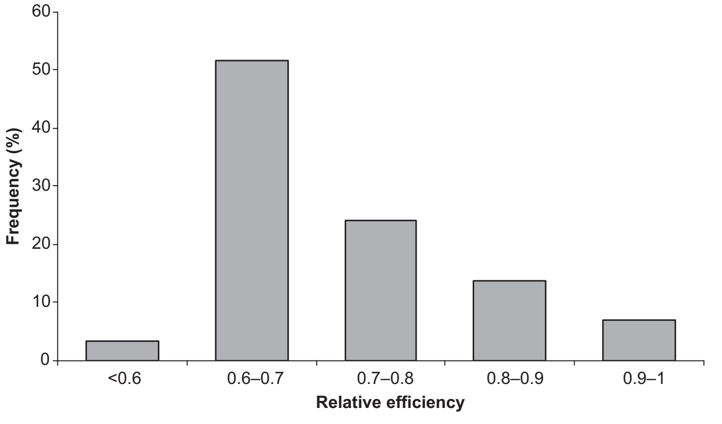

Figure 3 Relative economic efficiency of the vessels in the sample.

solution was a global optimum. Engine power was initially optimised keeping headrope length at the average observed level, and then headrope length was optimised given the optimal engine power. Except for the case of low fuel prices, the optimal headrope length was found to be equivalent to the average over the period of the data (i.e. $z^* = 1$).

The optimal relative engine power given the sample mean set of prices and average conditions was estimated to be 1.03, and given the error in the parameter estimates is not likely to be significantly different to 1.[5] The short- and long-run elasticities assuming $z^* = 1$ for both engine power and headrope length are presented in Table 4.

Most of the elasticities were not significant, but most had the expected sign. As expected, output supply was positively related to own price and negatively related to fuel prices, while input demand was positively related to output prices, but negatively related to own prices. Also as expected, the input demand and output supply are more price elastic in the longer term. Morishima elasticities of substitution between outputs were also estimated (Table 4) and indicated substitution between the two outputs in the long run (as expected given they are produced in separate time periods). Similarly, substitution potential between fuel use and engine power was also indicated.

5.2. Optimal vessel size given expected changes in stock size

A key aim of the paper was to estimate how vessels may adjust to the set of conditions relating to MEY and given that they are also able to maximise their individual profits. A number of assumptions were necessary to estimate the optimal output and input use under an ITQ regime. Stock conditions were assumed to be average for banana prawns. However, assuming MEYs can be achieved, stock levels are expected to be 27.6 per cent higher than the average

[5] A method for estimating the standard error of the estimate is given by Squires (1987). Given the proximity of the estimate to unity, a formal test was not undertaken.

Table 4 Own- and cross-price elasticities of input demand and output supply

Prices	Output supply		Input demand	
	Tiger prawns	Banana prawns	Fuel	Engine power
Short-run				
Tiger prawns	0.060	0.063	0.225	
Banana prawns	0.066	0.705**	1.437**	
Fuel	−0.126	−0.768**	−1.661**	
Long run				
Tiger prawns	0.296	0.626	0.336	0.292
Banana prawns	−0.271	2.106	2.504**	−1.036
Fuel	−0.514	−1.696*	−2.809*	−0.482
Engine power	−0.434	−0.638	−1.282	0.538
Morishima elasticities of substitution (long run)				
Tiger prawns		−2.377*		
Banana prawns	0.330			
Fuel				2.327
Engine power			−1.820*	

**Significant at the 5% level; *significant at the 10% level.

over the period of the data for the tiger/endeavour prawn group, based on the outputs of the bioeconomic model (Deng *et al*. 2008; Kompas *et al*. 2010). Prices of both fuel and prawns are also expected to change over time, and a range of price combinations was included in the analysis. The estimates of MEY from the bioeconomic model, however, were based on the assumptions that prawn prices would be 2.6 per cent higher than the average over the period of the data used in this analysis, and fuel prices would be 77 per cent higher (Deng *et al*. 2008; Kompas *et al*. 2010).

Under an ITQ system, it was also assumed that season length would cease to be a constraint as the negative relationship between season length and profits was an artefact of the input control system, and an optimal catch can be taken within the existing seasons. Similarly, the negative disembodied technical change was also ignored, as it was assumed that the management restrictions causing this could also be removed under the output control system.

The optimal vessel engine power was estimated under a range of price conditions (Figure 4a), and this is used to estimate the optimal catch of each species. The resultant estimates of optimal vessel size and individual output levels, and the impact of prices on these estimates, are illustrated in Figure 4. Given the price assumptions in the bioeconomic model and the associated stock size at MEY, vessels are likely to increase their engine power (and presumably their overall size) by around 20 per cent in the long run.

Fuel use is expected to decrease by around 20 per cent relative to the average over the period of the data for a wide range of prices (Figure 4b), suggesting that larger engines are partially being substituted for days fished. This particularly large decrease is mostly driven by the relatively high fuel prices.

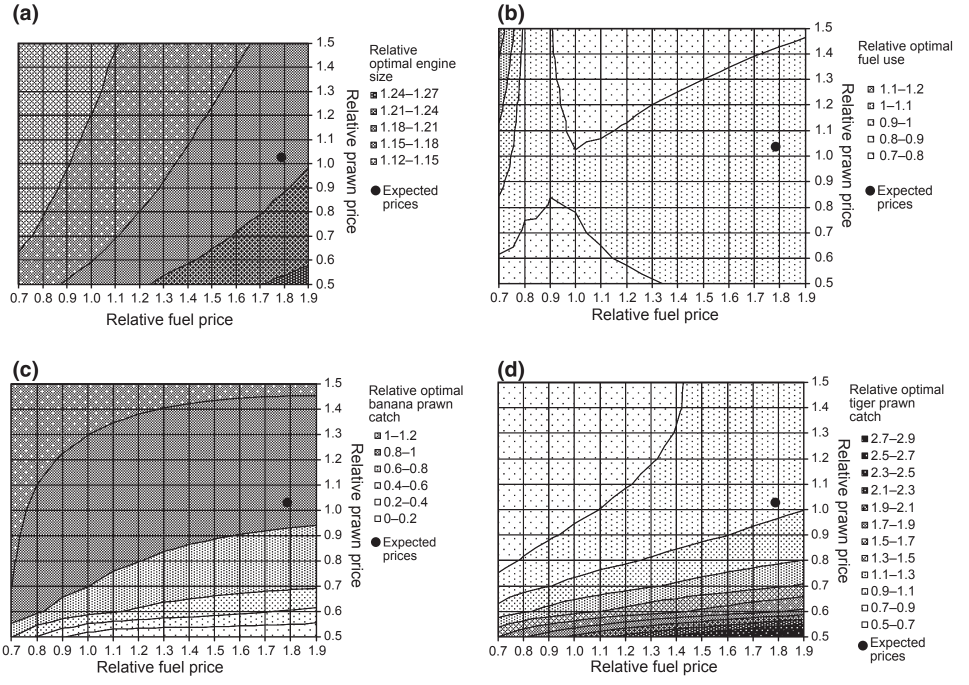

Figure 4 Optimal input use and catches: (a) engine power, (b) fuel use, (c) banana prawn catch and (d) tiger group catch.

However, lower levels of fuel consumption were optimal for all price scenarios (both inputs and outputs), suggesting that cost savings through effort reduction would more than offset reduced revenue arising from the subsequently lower catches.

The optimal individual catches per vessel of the two species groups are also lower, given the price assumptions.[6] There is a general apparent 'shift' from banana prawns to the more valuable tiger prawns as prawn prices decrease, and fuel prices increase. The optimal individual vessels' catch of banana and tigers prawns is around 80 and 85 per cent, respectively, of their average over the period 1994–1995 to 1995–1996, *ceteris paribus* at the assumed long-run relative fuel and prawn prices in the bioeconomic model (Figure 4c,d).

6. Discussion and conclusions

The northern prawn fishery is fairly unique in that maximising economic returns is an explicit management objective. The fishery is also dominated by

[6] As noted by a reviewer, the introduction of ITQs will result in a price for quota that has not been considered in the analysis. This may also affect optimal input usage as input demand is related to optimal output supply. However, as the optimal output is less than current harvest level, and quotas are likely to exceed the optimal output, then quotas are likely to be nonbinding and the shadow price effectively zero.

fishing companies, most of which have recently amalgamated into a single incorporated company to achieve economies in terms of input purchases and marketing of outputs. Hence, the motivation to maximise profits in the fishery is high. The move to ITQs will provide incentives for vessel owners to adjust their quota holdings as well as fishing activities to their most economically efficient configuration.

The results of the model are generally consistent with most other studies that suggest that fewer, larger vessels are likely to emerge from an ITQ system (Nostbakken 2006; Eggert and Tveteras 2007; Hoff and Frost 2007; Pascoe 2007; Asche *et al*. 2008). In most fisheries under ITQs, consolidation of quota results in a smaller fleet than pre-ITQ management (Campbell *et al*. 2000; Aslin *et al*. 2001; Stewart *et al*. 2006). Further, in most fisheries where ITQs have been introduced, TACs are initially lower than recent catches, which further creates incentives for vessels to adjust. In contrast, the potential autonomous adjustment that is generally assumed to occur as a result of ITQ management had already taken place through the recent buyback program. The optimal move to larger vessels in the NPF, if it occurs, is driven primarily by the increase in fuel prices and the resultant substitution of fishing power for fishing days.

The bioeconomic models of the fishery (Deng *et al*. 2008; Kompas *et al*. 2010) estimate that, given the price assumptions noted previously, the tiger prawn TAC at MEY would be 26 per cent higher than the average catch over the period of the data used in this analysis, and the endeavour prawn TAC would be 12 per cent higher.[7] In contrast, the results of the profit function suggest that individual vessels should seek to reduce their individual catch rather than to increase it under the same stock and price conditions. The fishers, however, are familiar with operating in a competitive environment where the incentives are to increase input use in an attempt to increase catches. With increasing TACs, the incentive to reduce effort and catch will directly conflict with the habit of increasing effort and catch. Habits are a strong determinant of behaviour in fisheries (Holland and Sutinen 2000), and effectively nonbinding TACs may result in the full potential economic benefits of ITQs not being achieved (Fox *et al*. 2006; Grafton *et al*. 2007).

The analysis was based on data prior to 2005–2006, which in turn was affected by the management structures in place during the period of the data. Management conditions in the fishery have since changed, and these may affect the results. In particular, the analysis was based on data that included a restriction on fishing for tiger prawns in the second season only. Tiger prawn stocks have improved in line with the earlier modelling (Punt *et al*. 2010), and the first season has been re-opened to tiger prawn fishing in recognition of the fact that the fleet would not be capable of taking the optimal catch, given the

[7] The more recent bioeconomic model of the fishery, based on a size structured rather than delay difference biological model, suggests slightly lower stocks and catches may be realised at MEY (Punt *et al*. 2010).

time constraints imposed. Consequently, there is value in redoing the analysis in several years hence to determine the effects of such changes on optimal behaviour as well as the effects of the fleet reduction that took place in 2005 and 2006.

The study highlights the importance of considering vessel behaviour when trying to estimate MEY in fisheries. In this case, the bioeconomic model-based estimates of MEY assumes the existing fleet is willing and able to increase their output as stocks recover, whereas this study suggests that, under the management conditions faced at the time by the fishers, profit-maximising fishers should aim to decrease their individual output in response to falling output prices and relatively high fuel prices. Hence, the assumptions underlying the estimation of MEY are potentially inconsistent with the incentives facing the fishers.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. The banana prawn fishery and implications of CPUE as a stock index.

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