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ABSTRACT

This paper uses data from an actual fishery to construct a tractable and dynamic model to compare expected profit and its variance, optimal stock size, optimal harvest rate and optimal fishing effort under different management regimes under uncertainty. The results provide a comparison of instrument choice between a total harvest control and a total effort control under uncertainty, an original method to evaluate the tradeoffs between profits and other criteria in a dynamic context, and provide guidance as to the relative merits of catch and effort controls in fisheries management.

Keywords: Fisheries management, uncertainty
JEL Codes: Q22, D81

I. INTRODUCTION

A major focus of fisheries economics is designing the appropriate set of instruments to achieve desired management objectives, such as sustainability and economic efficiency. An important consideration when choosing between alternatives is the uncertainty associated with total harvest or total allowable catch (TAC) controls, and the uncertainty associated with effort controls, denoted by total allowable effort (TAE). The principal causes of uncertainty are: unexpected realizations in terms of the stock size such that the TAC is set at too high or too low a level, and unexpected realizations in terms of the catch-effort relationship such that fishing effort is set at an inappropriate level.

Uncertainty in stock size is often cited as one of the main limitations of TAC controls in fisheries. This is because some knowledge of stocks is required to be able to set a TAC that, in turn, also determines any quota allocations vessels may obtain under an individual transferable quota system. If the TAC is set too high because the stock is less than expected, fisheries managers run the risk of putting excessive fishing pressure on stocks in low abundance years, with the potential for substantial reductions in the total catch in the future. If the TAC is set at too low a level because fish stocks are greater than expected, managers reduce the profitable opportunities available to fishers.

A similar problem exists in terms of effort controls except the uncertainty arises in the catch-effort relationship, usually denominated by the catch per unit of effort (*CPUE*). If the *CPUE* is higher than expected then a fishery manager risks setting a TAE that is too large and thus places at risk the sustainability of fish stocks, and also increases the per unit cost of fishing in future years. If the *CPUE* is less than expected then the TAE will be set at too low a level, this will also reduce the profitable opportunities available to fishers. In both cases (TAC or TAE controls) unexpected realizations in stock size or in the *CPUE* will result in errors and a failure to achieve management objectives.

In this paper we examine the relative merits of TAC versus TAE controls using data from an actual fishery. Our work builds on the insights of Hannesson and Steinshamn (1991), Quiggin (1992) and Danielsson (2002 a,b). In earlier work, Hannesson and Steinshamn (1991) in a single-period model compared expected profits with a TAC and with a TAE and, under reasonable assumptions about the curvature of the revenue and cost functions, found that a TAC gives both higher expected revenues and also harvesting costs relative to a TAE when the only source of uncertainty is stock size. Quiggin (2002) used the same one-period model to show that, *if* stocks are independently and identically distributed, there exists a constant TAE control that yields a higher profit than a fixed TAC. Danielsson (2002a,b) added another type of uncertainty in terms of the *CPUE*, in addition to uncertainty with respect to stock size, so as to make a fairer comparison of the two instruments. He found that, all else equal, the greater the variability in the *CPUE* relative to the growth in the stock the greater is the comparative advantage of a TAC relative to a TAE.

In this paper we use data from the Northern Prawn fishery (NPF) of Australia to compare the relative merits of TAC and TAE controls in the presence of uncertainty, in an explicit dynamic model. We do not consider the incentives issues of input versus output controls, nor do we examine differences in costs of management because these have been examined in detail elsewhere (Grafton et al. 2006). As far as we are aware, our analysis is the first to make dynamic comparisons between TAC and TAE controls under uncertainty using actual fisheries data. We also extend the results of Danielsson into a fully dynamic model that examines the effects on the variance of expected profits, fish stocks, the harvest rate and fishing effort. We also provide, for the first time, a practical method to compare TAC and TAE controls under uncertainty.

Section 2 provides a brief description of the NPF. Section 3 sets out the theoretical framework, including the biological model, the relationship between harvest and catch per unit of effort, the economic model and the optimizing framework to compare TAC and TAE controls. We use a genetic algorithm in Section 4 to solve the model for a set of parameters and compare differences between expected profit, stock size, harvest rate and fishing effort under TAC and TAE controls. Section 5 provides additional scenarios to compare the two instruments while Section 6 concludes.

II. THE AUSTRALIAN NORTHERN PRAWN FISHERY

The NPF occupies a very large area of the ocean off Australia’s northern coast. The fishery extends from the low water mark to the outer edge of the Australian fishing zone (AFZ) along approximately 6,000 kilometres of coastline between Cape York in Queensland and Cape Londonderry in Western Australia (AFMA, 2002).

There are more than fifty species of prawn that inhabit Australia's tropical northern coastline, but only about nine species of prawns are harvested. Three species (the white banana prawn *Fenneropenaeus merguiensis*¸ the brown tiger prawn *Penaeus esculentus*, and the grooved tiger prawn *P. semisulcatus*) account for almost 80 per cent of the total annual landed catch weight from the fishery (AFMA, 2002). The banana prawns are caught are different times of the year to the two main species of tiger prawns. When fishing for tiger prawns, vessels utilize twin-rigged otter trawl nets that sweep the ocean behind the fishing vessel. The netting at the mouth of the net is hung from a headrope at the top and a footrope stretched between otter boards. Operators can regulate the width of their net according to the angle and lateral force of the net otter boards (AFMA, 1999).

The fishery is managed under the Northern Prawn Fishery Management Plan 1995. To date, a series of input controls have been used to regulate the fishery. These controls include limited entry and gear restrictions (through the issuing of Statutory Fishing Rights or SFRs), a system of spatial and temporal closures, and by-catch restrictions (AFMA, 2002). The SFRs control fishing capacity by placing limits on the numbers of boats and the amount of gear permitted in the fishery. In its relatively short history the fishery has experienced a significant variation in catch. Low prawn prices reduced profitability in the 1980s and led to restructuring of the fleet in the late 1980s and early 1990s. The fleet structure has also changed gradually since the 1970s with a transition from wooden trawlers with brine tanks and iceboxes toward larger, purpose-built, steel freezer trawlers with high catch and carrying capacities.

III. BIOECONOMIC MODELS OF THE FISHERY

To compare TAC and TAE controls under uncertainty we need a biological model of the stock recruitment relationship and a specification regarding the relationship between fishing effort and the total harvest.

Stock-Recruitment Relationship

The spawning stock-recruitment relationship is based on Ricker's equation (Ricker, 1954), i.e.,

$$R_t = \alpha_1 \hat{S}_{t-1} e^{\beta_1 \hat{S}_{t-1}} + \xi_1 \tag{1}$$

where R_t is the total number of recruits produced in year t and $\hat{S}_{t-1}$ is the spawning stock of the previous year (estimated as the number of prawns). The parameters α_1 and β_1 determine the relationship between recruitment and the number of spawners in the previous year while the term ξ_1 represents uncertainty, or the stochastic behavior of the spawning stock-recruitment relationship.

The underlying relationships within the stock-recruitment relationship must also be modeled. First, the spawning stock is taken as a proportion (γ) of the total female stock, assuming that female prawns constitute half of the total stock of prawns and the sex ratio (males to females) is 1:1, i.e.,

$$\hat{S}_{t-1} = \left(\gamma \; S_{t-1}\right)/2 \qquad (2).$$

Following Penn *et al.* (1995) and Wang and Die (1996) the spawning stock $\hat{S}_t$ is assumed to be the result of annual recruitment R_t and also fishing effort, defined as

$$\hat{S}_t = \alpha_2 R_t e^{-\beta_2 (F_t + m)} \tag{3}$$

where F_t is fishing mortality at year t and m is the annual natural mortality rate. Using existing studies from the NPF, Wang and Die (1996) define fishing mortality in year t as follows:

$$F_t = q * E_t = q * B_t * N_t \tag{4}$$

where q is the 'catchability coefficient' and E_t is fishing effort at year t.

Fishing effort is determined as total 'standard' boat days in the fishery, which is a multiple of total 'standard' boats (B_t) and nominal fishing days in the season (N_t). In the NPF, one unit of fishing effort is defined as the daily effort of a 'standard' boat that equates boat day units between large and small vessels. In practical terms, this capacity can be measured by boat engine power and a measure of hull units, or the length or the weight of boat. For example, in the NPF boat size is measured in terms of A-units, as a simple linear combination of a kilowatt of engine power and a cubic meter of hull. Thus if we define a standard boat size as $\bar{A}$ units then the total standard boat numbers at year t is given by

$$B_t = \sum_{i=1}^{M} \frac{A_{it}}{\overline{A}} \tag{5}$$

where M is the number of boats in the fishery and A_i the size of boat i in units in year t. If there is technological change then (4) needs to be adjusted such that

$$F_t = q * E_t = q * TEC_t * B_t * N_t \tag{6}$$

where TEC_t measures the change in technology at year t.

Catch per unit of effort (CPUE)

To assess the effect of uncertainty on *CPUE*, we must also specify a relationship between harvest or total catch and the biology of the fishery. Based on previous work on the NPF, Wang and Die (1996) use the following specification for the harvest rate

$$h_t = \alpha_3 R_t (1 - e^{-\beta_3 (F_t + m)}) \tag{7}$$

where h_t is the annual catch in tonnes that increases asymptotically to a maximum of $\alpha_3 R_t$ as fishing effort tends to infinity (Wang and Die, 1996).

Using (7) *CPUE* at a given point in time is:

$$CPUE_t = \frac{h_t}{E_t} = (\alpha_3 R_t (1 - e^{-\beta_3 (F_t + m)})) / (E_t) + \xi_2 \qquad (8)$$

where ξ_2 represents stochastic behavior associated with *CPUE*.

Economic Model

To operationalize the bioeconomic model, further specifications are required in terms of total revenue and total costs. Annual total revenue of the fishery is defined as the multiple of annual fish harvest and the annual (average) price of fish,

$$TR_t = p_h h_t \qquad (9)$$

where p_h is the price of fish drawn from an inverse demand curve. Following Danielsson (2002a) and Campbell, *et al.*, (1993) this price is determined using the following specification with data from the period 1990-2003 (ABARE, 1990-2003),

$$p_h = p_0 (H_0 / h_t)^{1/\varepsilon} \qquad (10)$$

where ε is the elasticity of demand for catch and p_0 is the unit price of the catch when the volume of the catch is H_0.

Annual total cost of the fleet is assumed to be the sum of labor, material, capital and other costs. Labor costs are represented as a share of total revenue because of the share system for the remuneration crew that also accounts for material costs such as packaging and gear maintenance expenditures. Capital costs, defined as the sum of depreciation and the annual opportunity cost of boat capital value, and other costs (of which fuel is a major component) are assumed to depend on fishing effort that is defined as total ‘standard’ boat-days with the number of ‘standard’ boats (B_t) computed as per equation (5). Thus that total harvesting costs are expressed as

$$TC_t = c_F + c_L h_t p_h + c_M h_t p_h + c_K E_t + c_O E_t \tag{11}$$

where c_L and c_M are the share cost of labor and materials per each Australian dollar of output, c_K and c_O are, respectively, the average capital and other costs per unit of effort, and c_F is a fixed cost component. The average capital cost of a unit of effort (c_K) is estimated by dividing total capital costs by total effort. Average other costs (c_O) per unit of effort are estimated by dividing total other costs by total fishing effort.

Using (10) and (11) the annual fishery profit is as

$$\Pi_t = p_h h_t - (c_F + c_L h_t p_h + c_M h_t p_h + c_K E_t + c_O E_t) \qquad (12).$$

Optimization Model

The stated aim of the Australian government is to maximize economic efficiency in its fisheries subject to a long-term sustainability constraint. Consequently, we specify that the management objective is to maximise expected profits over time. The control variable in the case of TAE control is fishing effort (E_t), defined as the number of nominal days fished, while with a TAC the control is exercised via the total harvest (h_t). Thus with a TAE, assuming fishing effort is observable and also enforceable the problem is to maximize

$$\max_{E_t} \sum_{\mathrm{i=1}}^{\mathrm{T}} \Pi_{\mathrm{t}} = \sum_{i=1}^{T} p_h h_t(E_t) - (c_F + c_L h_t(E_t) p_h + c_M h_t(E_t) p_h + c_K E_t + c_O E_t) \tag{13}$$

If future profits are discounted and if (6), (7) and (1) are substituted into equation (13) we obtain the modified objective function that the regulator maximizes,

$$\max_{E_t} \sum_{\mathrm{i=1}}^{\mathrm{T}} \hat{\Pi}_{\mathrm{t}} = \sum_{i=1}^{T} \frac{1}{(1+\delta)^i} \left((p_h - c_L - c_M) \alpha_3 \alpha_1 \hat{S}_{t-1} e^{\beta_1 \hat{S}_{t-1}} (1 - e^{-\beta_3 (qE_t + m)}) - c_K E_t - c_0 E_t - c_F \right) \tag{14}$$

where δ is the discount rate and $\widehat{\Pi}_t$ is the net present value of profit at year *t*.

The problem for the regulator that uses exclusively a TAC control is to maximize

$$\max_{h_t} \sum_{\mathrm{i=1}}^{\mathrm{T}} \hat{\Pi}_{\mathrm{t}} = \sum_{i=1}^{T} \left(\frac{1}{(1+\delta)^t} \right) (p_h h_t - (c_F + c_L h_t p_h + c_M h_t p_h + c_K E_t + c_O E_t) \tag{15}$$

subject to equations (1)-(3). Solving (14) or (15) also requires that spawning stock at the period 0 ($\hat{S}_0$) be known and an appropriate transversality condition which we specify as $\Pi_T = 0$

Model Parameters

To make the comparisons between TAC and TAE controls under uncertainty we need to specify parameter values for (14) and (15). Many of these values are in terms of the stock-recruitment model given in (1) and fishing mortality in (6). The parameters for the two main types of prawns (brown tiger and grooved tiger prawns) caught in the fishery are provided in Table One. Further details on the sources and calculations used to derive the parameters are provided in Kompas and Che (2003).

In addition to using parameter values from other studies, the stock-recruitment equation, given by equation (1) and the *CPUE*, given by equation (8), were estimated using annual time-series database over the period 1971-2000. Initial values are drawn from measures in Wang and Die (1996). Both equations were estimated using Non-Linear Least Squares (NLS) estimation techniques in Microfit 5.1. The estimating equation for the stock recruitment relationship is

$$R_t = \alpha_1 \hat{S}_{t-1} e^{\beta_1 \hat{S}_{t-1}} + u_t(\bar{u}, \xi_3) \tag{16}$$

where u_t is the residual of the regression with mean value $\bar{u}$ and standard deviation ξ_3. The estimating equation for the *CPUE* relationship is as follows:

$$CPUE_t = \frac{h_t}{E_t} = (\alpha_3 R_t (1 - e^{-\beta_3 (F_t + m)})) / (E_t) + u_t (\overline{u}, \xi_4) \qquad (17)$$

where u_t is the residual of the regression with the mean value $\overline{u}$ and standard deviation ξ_4. The estimated results for the two equations are provided in Table Two where the standard deviation has been converted to a percentage deviation.

The estimated parameters and standard deviations of the regression equations for (16) and (17) are provided in Table Two. The results both support the previous biological studies and also the application of the *CPUE* equation given by (8). Table Two also shows that the variance in the stock-recruitment relationship is smaller in all cases than that for *CPUE*.

IV. RESULTS OF THE BIOECONOMIC MODELS

Given the nonlinear relationships in the bioeconomic models and stochastic nature of the problem a genetic algorithm (Goldberg 1989) imported into MAPLE 10.0 was used to solve for the optimal solution to the TAE control problem in (14) and the TAC control problem in (15). The optimal solutions for a non-stochastic ($\xi_3 = \xi_4 = 0$) version of the model and also a stochastic version using the estimated standard deviations in Table Two are presented in Table Three. In both cases the discount rate is set equal to zero and the time horizon is 50 years, long enough to guarantee that optimal results are sufficiently close to their steady state values before diverting to meet a terminal condition in year 50. The terminal condition is such that the value of profits at year 50 goes to zero. As a result near the terminal state or year 50, effort and harvest increase and stock size falls dramatically as the terminal condition of zero profits is met.

The base model in Table Three shows that, in the absence of uncertainty and with perfect information and enforcement, the TAC and TAE controls yield identical results. By contrast, using the estimated measures of uncertainty in the fishery there is a difference between the two instruments, as shown in the stochastic recruitment and CPUE model in the lower half of Table Three. Given that the estimated standard deviation in the stock recruitment relationship is lower than in the *CPUE* relationship a TAC control outperforms a TAE control in terms of expected profits by about A$13 million for the fishery as a whole, or approximately A$2,200 per boat per year. In addition, the standard deviation in mean expected profit is less than a third with a TAC versus a TAE control while the stock size with a TAC is also higher than with a TAE, and also has a lower standard deviation.

The optimal solutions for the case with a social-economic discount rate of three per cent are reported in Table 4. Both cases (without and with uncertainty) indicate more catch earlier in the planning horizon and consequently smaller ‘near’ steady state stocks than in cases without discounting. With discounting, future catch is valued less today generating a preference for increases in catch in transition than in the steady state. Harvest and fishing effort per boat per year in the base case are thus higher for the discounted case being some 2,350 tonnes and 77 days while they are 2,240 tonnes and 70 days without discounting. To maintain catch at higher levels the stock must be smaller, indicating that discounting is less ‘conservationist’ than the case of no discounting. As with the case of a zero discount rate, a TAC is preferred to TAE control because it generates a higher mean expected profit, a much lower standard deviation of mean expected profits, a higher stock size and lower fishing effort in terms of total boat days.

V. UNCERTAINTY SCENARIOS AND INSTRUMENT CHOICE

To further analyze the effects of estimated uncertainties on instrument choice we generate three counterfactual scenarios. In case one, we use the estimated standard deviation in the stock recruitment relationship provided in Table Two, but set the standard deviation in the *CPUE* relationship equal to zero. In the second scenario, we set the standard deviation in the stock recruitment relationship equal to zero but use the estimated standard deviation in the *CPUE* relationship from Table Two. In the third case, we assign the estimated standard deviation of the *CPUE* relationship in Table Two to the stock-recruitment relationship, and assign the estimated standard deviation of the stock recruitment relationship in Table Two to the *CPUE* relationship.

The optimal solutions for the three cases are provided in Table 5 without discounting. In case one, both TAC and TAE controls generate higher expected profits than with the actual uncertainty in the fishery. As we would expect, given there is no uncertainty in the

CPUE relationship ($\xi_4 = 0$), the TAE control is preferred over the TAC control in terms of expected mean profits. In this case, the TAE control generates a higher profit of around A$ 1,500 per boat per year (nominal value). However, even in this extreme scenario the TAC control still manages to generate a lower variation in expected profits and a higher stock size than a TAE control.

In case two, there is no stochasticity in the stock recruitment relationship ($\xi_3 = 0$) but the estimated standard deviation for the CPUE relationship of 25.23 per cent and 23.25 per cent for Brown and Grooved prawns is retained. In this scenario, the TAC control provides a higher expected mean profit of about $3,800 per boat per year (nominal value) compared to TAE control, a lower optimal stock size at the steady state and also smaller variance for expected profits than TAE control.

In case three, the stochastic levels of stock and *CPUE* are swapped such that the standard deviation of the stock recruitment relationship is higher than the standard deviation of the *CPUE* relationship ($\xi_3 > \xi_4$). In this scenario, unlike the results reported in Table Three, the TAE control generates a higher expected mean profit compared to a TAC control. However, the standard deviation of expected profits is almost as twice as large with the TAE control and the stock size is slightly smaller. Thus it is not clear, given risk averse fishers, whether a TAE would be the preferred instrument despite the fact it generates higher expected total profits.

A summary of the effects of TAC and TAE controls under the three uncertainty scenarios, the base case with no uncertainty, and also with the actual estimated uncertainties in the stock recruitment and *CPUE* relationship is provided in Table Six. Our results are consistent with the Danielsson (2002b) one-period model in that we show that if the standard variation is greater (less than) in the stock recruitment relationship relative to the *CPUE* relationship then the mean expected profits at the optimum solution are lower (higher) with TAC versus TAE controls. However we also show, for the first time, that there are important differences in terms of variation in profits, stock size, harvest rate and level of fishing effort between TAC and TAE controls under uncertainty. At least for the estimated stock recruitment and *CPUE* relationships that exist in the NPF, we find that even when the TAE control is preferred on the basis of expected profits when $\xi_3 > \xi_4$, the standard deviation of expected profits is still much less with a TAC control while the stock size is higher, and both the harvest rate and level of fishing effort are less. Thus if fishers are risk averse and/or if fishery managers attach a greater value to stock sizes because of resilience to environmental shocks (Grafton, Kompas and Lindenmayer 2005) a TAC control may still be preferred to a TAE control even if total expected profits are higher.

Overall, the results show important differences between the two instruments with uncertainty, and that even in the case when a TAE generates a higher expected mean profit it not clear that it would necessarily be preferred over a TAC control. The relative merits of TAC control are further highlighted if we consider the possibility of ‘effort creep’ where the regulator is not able to effectively control fishing effort because of the incentives of fishers to substitute to unregulated fishing inputs. For instance, in an earlier study Kompas, Che and Grafton (2004) have shown that such input substitution in the NPF has resulted in lower technical efficiency and higher than optimal levels of fishing effort.

VI. CONCLUDING REMARKS

In this paper we provide the first dynamic comparison of instrument choice in fishing between a total harvest control and a total effort control under uncertainty. Using data from the Northern prawn Fishery of Australia we provide a methodology to compare the two instruments. In a fifty-year planning period, various scenarios are examined to compare optimal outcomes with a total harvest and total effort controlled fishery where the uncertainty is estimated from known stock-recruitment relationships and catch and effort data.

A base case scenario with no uncertainty shows that the two instruments — total harvest or total effort — give identical outcomes provided there is perfect monitoring and enforcement. Using the estimated uncertainties in the stock recruitment and catch per unit of effort relationships we find that a total harvest control, with and without discounting, is preferred in that it generates a higher total profit, lower variance of expected profits, higher stock size, and lower harvest rate and levels of fishing effort compared to a total effort control. This is because there is greater variation in the estimated catch per unit of effort relationship than in the stock recruitment relationship.

Using different specifications regarding the uncertainties, three counterfactual scenarios are analyzed. These scenarios show that, for the Northern Prawn Fishery, even when TAE generates a higher total expected profit it has a higher variance in expected profits, a smaller optimal stock size, and higher optimal harvest rate and fishing effort than a TAC control. Overall, we provide a tractable method to compare management instruments in actual fisheries under uncertainty, show the nature of the tradeoffs between profits and other management criteria in a dynamic context, and give guidance on the relative merits of TAC and TAE controls.

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Table One: Parameter Values Used in the Optimization Models

Parameters	Source	Units	Parameter Values	
			Brown Tiger	*Grooved Tiger*
Biological model				
$\hat{S}_0$	CSIRO (2002a)	*million prawns*	15	18
R_1		*million prawns*	187	309
α_1	Wang & Die (1996)		14.41	45.96
β_1	Wang & Die (1996)		0.0096	0.0548
α_2	Wang & Die (1996)		0.111	0.047
β_2	Wang & Die (1996)		0.354	0.302
m	Wang (1999), Wang & Die (1996)	*annual rate*	0.045	0.045
γ	Crocos (1987a, 1987b)	*annual rate*	0.3	0.2
Fishing model				
α_3	Wang & Die (1996)		14.08	15.18
β_3	Wang & Die (1996)		0.494	0.544
			Brown and Grooved Tiger Prawn	
Number of vessels	AFMA (2002)	*number*	120	
Standard A-unit vessel	CSIRO (2002b)	*A-unit*	400	
Catchability rate of one unit fishing effort	Wang (1999)	*CPUE(kg/day)*	8.8*(10^-5)	
Economic model				
The initial price (P_0)	ABARE (2003)	*\$/kg*	30	
The initial catch (H_0)	ABARE (2003)	*ton*	1,800	
Price elasticity of demand	Authors' calculations		15	
Share of labour cost per \$1 output	ABARE (1994-2001)		0.26	
Share of materials costs per \$1 output	ABARE (1994-2001)		0.25	
Average capital cost per a unit of fishing effort (c_K)	ABARE (1994-2001)	*\$ per 'standard' boat- day*	884	
Average other costs per unit of fishing effort (c_O)	ABARE (1994-2001)	*\$ per 'standard' boat- day*	1,180	

Table Two: Non-Linear Estimated Results for the Ricker Equation (16) and the *CPUE* Equation (17) Using 1971-2000 Data

Ricker Equation	**Brown Tiger**	**Grooved Tiger**
Coefficient α_1		
Estimate	14.41	45.96
t-ratio	6.09	9.26
p-value	0.000	0.000
Coefficient β_1		
Estimate	0.0096	0.0548
t-ratio	3.16	4.16
p-value	0.004	0.000
Standard deviation of the residuals of the regression (ξ_3)	21.45 %	15.92%

***CPUE* Equation**	**Brown Tiger**	**Grooved Tiger**
Coefficient α_3		1
Estimate	14.03	15.18
t-ratio	2.91	1.94
p-value	0.007	0.063
Coefficient β_3		
Estimate	0.494	0.544
t-ratio	3.04	1.5
p-value	0.005	0.147
Standard deviation of the residuals of the regression (ξ_4)	25.53%	23.155%

Table Three: Optimal Solutions of the Base-Case and Stochastic Models without Discounting

		Unit	TAC control	TAE control
1	**Base model**			
	Total Expected Profit (mean value)	*A$*	732,000,000	732,000,000
	Mean values at steady state			
	Total stock size		308	308
	• Stock size of Brown Tiger	*millions*	205	205
	• Stock size of Grooved Tiger	*millions*	103	103
	Annual harvest	*tonnes*	2,240	2,240
	Number of boats in a year	*boat*	120	120
	Fishing day per boat per year	*days*	70	70
	Total boat days per year	*boat-day*	8,400	8,400
	The average values per year			
	Total stock size		304	304
	• Stock size of Brown Tiger	*millions*	198	198
	• Stock size of Grooved Tiger	*millions*	106	106
	Annual harvest	*tonnes*	2,140	2,140
	Number of boats	*boat*	120	120
	Fishing day per boat per year	*days*	67	67
	Total boat days	*boat-day*	8,040	8,040
2	**Stochastic recruitment and CPUE model**			
	Total Expected Profit (mean value)	*A$*	658,000,000	645,000,000
	• Standard of deviation	*millions*	40,000,000	152,000,000
	Mean values at steady state			
	Total stock size	*millions*	330	324
	• Stock size of Tiger Brown	*millions*	227	219
	• Stock size of Tiger Grooved	*tonnes*	106	105
	Annual harvest	*tonnes*	2,060	2,100
	Number of boats in a year	*boat-day*	120	120
	Fishing day per boat per year	*days*	61	63
	Total boat days per year at the steady state	*boat-days*	7,320	7,560
	The average values per year			
	Total stock size	*millions*	321	317
	• Stock size of Brown Tiger	*millions*	213	211
	• Stock size of Grooved Tiger	*tonnes*	108	106
	Annual harvest	*tonnes*	1,950	2,070
	Number of boats	*boat-day*	120	120
	Fishing day per boat per year	*days*	58	62
	Total boat days	*boat-days*	6,960	7,440

Table Four: **Optimal Solutions of the Base-case and Stochastic Models with a Discount Rate (δ = 3 %)**

		Unit	**TAC control**	**TAE control**
1	**Base model**			
	Total Expected Profit (mean value)	*A$*	365,000,000	365,000,000
	Mean values at steady state			
	Total stock size		302	302
	• Stock size of Brown Tiger	*millions*	203	203
	• Stock size of Grooved Tiger	*millions*	99	99
	Annual harvest	*tonnes*	2,350	2,350
	Number of boats in a year	*boat*	120	120
	Fishing day per boat per year	*days*	77	77
	Total boat days per year	*boat-day*	9,240	9,240
	The average values per year			
	Total stock size		298	298
	• Stock size of Brown Tiger	*millions*	196	196
	• Stock size of Grooved Tiger	*millions*	102	102
	Annual harvest	*tonnes*	2,250	2,250
	Number of boats	*boat*	120	120
	Fishing day	*days*	73	73
	Total boat days	*boat-day*	8,760	8,760
2	**Stochastic recruitment and CPUE model**			
	Total Expected Profit (mean value)	*A$*	328,000,000	326,000,000
	• Standard of deviation	*millions*	21,000,000	79,000,000
	Mean values at steady state			
	Average stock size	*millions*	329	322
	• Stock size of Tiger Brown	*millions*	223	217
	• Stock size of Tiger Grooved	*tonnes*	106	105
	Annual harvest	*tonnes*	2,080	2,120
	Number of boats in a year	*boat-day*	120	120
	Fishing day per boat per year	*days*	63	64
	Total boat days per year at the steady state	*boat-days*	7,560	7,680
	Average values per year			
	Total stock size	*millions*	320	315
	• Stock size of Brown Tiger	*millions*	216	208
	• Stock size of Grooved Tiger	*tonnes*	104	105
	Annual harvest	*tonnes*	2,020	2,060
	Number of boats	*boat-day*	120	120
	Fishing day	*days*	61	63
	Total boat days	*boat-days*	7,320	7,560

Table Five: Optimal solutions Under Three Uncertainty Scenarios

	Unit	TAC control	TAE control
Case One			
Total Expected Profit (mean value)	*A$*	661,000,000	670,000,000
Standard Deviation of Expected Profits		31,000,000	46,000,000
Mean values at steady state			
Total stock size	*millions*	327	316
Annual harvest	*tonnes*	2,070	2,160
Number of boats in a year	*boat*	120	120
Fishing day in a year	*days*	62	67
Total boat days per year	*boat-day*	7,440	8,040
The average values per year			
Total stock size		321	313
Annual harvest	*tonnes*	1,970	2,100
Number of boats	*boat*	120	120
Fishing day	*days*	59	64
Total boat days	*boat-day*	7,080	7,680
Case Two			
Total Expected Profit (mean value)	*A$*	728,000,000	705,000,000
Standard Deviation of Expected Profits		22,000,000	145,000,000
Mean values at steady state			
Total stock size	*millions*	312	315
Annual harvest	*tonnes*	2,200	2,100
Number of boats in a year	*boat*	120	120
Fishing day in a year	*days*	69	64
Total boat days per year	*boat-day*	8,280	7,780
The average values per year			
Total stock size		305	309
Annual harvest	*tonnes*	2,140	2,060
Number of boats	*boat*	120	120
Fishing day	*days*	67	63
Total boat days	*boat-day*	8,040	7,560
Case Three			
Total Expected Profit (mean value)	*A$*	603,000,000	615,000,000
Standard Deviation of Expected Profits		55,000,000	119,000,000
Mean values at steady state			
Total stock size	*millions*	331	321
Annual harvest	*tonnes*	2,000	2,180
Number of boats in a year	*boat*	120	120
Fishing day in a year	*days*	58	67
Total boat days per year	*boat-day*	6,960	8,040
The average values per year			
Total stock size		323	319
Annual harvest	*tonnes*	1,900	2,000
Number of boats	*boat*	120	120
Fishing day	*days*	56	61
Total boat days	*boat-day*	6,720	7,320

Table Six: Summary of Profit, Stock, Harvest and Fishing Effort Impacts of TAC and TAE Controls Under Different Scenarios

Scenario	**Total Expected Profit** (Π)	**St. Dev. Expected Profit** (σ)	**Effects of management options at steady state**		
			Stock Size (S)	**Harvest** (h)	**Effort** (E)
1. Base Case ($\xi_3 = \xi_4 = 0$)	$\Pi_{TAC} = \Pi_{TAE}$	Not Applicable	$S_{TAC} = S_{TAE}$	$h_{TAC} = h_{TAE}$	$E_{TAC} = E_{TAE}$
2. Estimated ξ_3 values, $\xi_4 = 0$	$\Pi_{TAC} < \Pi_{TAE}$	$\sigma_{TAC} < \sigma_{TAE}$	$S_{TAC} > S_{TAE}$	$h_{TAC} < h_{TAE}$	$E_{TAC} < E_{TAE}$
3. Estimated ξ_4 value, $\xi_3 = 0$	$\Pi_{TAC} > \Pi_{TAE}$	$\sigma_{TAC} < \sigma_{TAE}$	$S_{TAC} < S_{TAE}$	$h_{TAC} > h_{TAE}$	$E_{TAC} > E_{TAE}$
4. Estimated ξ_3 and ξ_4 values	$\Pi_{TAC} > \Pi_{TAE}$	$\sigma_{TAC} < \sigma_{TAE}$	$S_{TAC} > S_{TAE}$	$h_{TAC} < h_{TAE}$	$E_{TAC} < E_{TAE}$
5. Estimated ξ_3 and ξ_4 values are reversed in Equations (16) and (17)	$\Pi_{TAC} < \Pi_{TAE}$	$\sigma_{TAC} < \sigma_{TAE}$	$S_{TAC} > S_{TAE}$	$h_{TAC} < h_{TAE}$	$E_{TAC} < E_{TAE}$