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Management strategies for short lived species: The case of Australia's Northern Prawn Fishery 3. Factors affecting management and estimation performance

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Abstract

Management strategies for tiger prawns, *Penaeus semisulcatus* and *P. esculentus*, in Australia's Northern Prawn Fishery (NPF), are evaluated in terms of conservation- and economic-related performance measures. A two-stage process is used to determine the factors to which these performance measures are most sensitive. The first stage involves identifying the possible factors and their interactions, constructing a partial factorial design to allow the impact of first- and second-order interactions on the performance measures to be identified, and analysing the resultant performance measures using generalised linear models. The second stage entails an experiment based on a balanced design of the possible combinations of the key factors. The factors found to have the greatest impact on the performance measures are: (a) how fishing efficiency has changed over time and whether or not the assessment is based on the correct trend in fishing efficiency, (b) the catchability coefficient used to convert from fishing effort to fishing mortality, (c) the difference between the intended fishing effort and the actual fishing effort expended (implementation error), and (d) whether recruitment is spatially correlated among stocks or not.

Keywords: Input controls; Management Strategy Evaluation; Monte Carlo simulation; Multi-species modeling; Northern Prawn Fishery; Spatial structure

1. Introduction

Australia's Northern Prawn Fishery (NPF) is an input-controlled multi-stock and -species fishery targeting predominantly tiger and banana prawns. A fleet of less than 100 vessels trawls an area of about 200,000 km^2 (Mick Haywood, CSIRO, personnel communication). Management of the target species is through limits on the length of the fishing season (including a temporal closure that divides the year into two periods) and a system of individual tradeable gear (fishing effort) units that controls the total amount of headrope length in the fleet. At present, the status of the two species of tiger prawns (*Penaeus semisulcatus* and *P. esculentus*) is assessed using a weekly delay-difference model that treats each species separately (Dichmont et al., 2003a). The assessment involves estimating annual recruitment and indices of spawning stock size from catch and fishing effort data, and using these estimates to estimate the parameters of a stock–recruitment relationship.

In common with many fisheries worldwide, the NPF does not have a long-term fishery-independent index of abundance so management is based on inferences based on fitting models to catch and effort data. This, combined with the longevity of the target species and the input control nature of the fishery, makes estimation of the values for some of parameter of the assessment model difficult. For example, it has proved impossible to estimate the extent to which fishing power has changed over time (Dichmont et al., 2003b). As a result, stock assessments are conducted for several scenarios related to this (bounded by the "Base Case High" (H) and "Base Case Low" (L) scenarios). A second complication is that the data are not informative about the catchability coefficient (the constant of proportionality between fishing effort and fishing mortality) so assessments are based on

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catchability coefficients estimated from auxiliary analyses (e.g. Wang (1999)). Nevertheless, Dichmont et al. (2003a) found that recruitment and spawning stock size are estimated robustly and had declined substantially by 2000, but that the status of the resource relative to MSY-based reference points was uncertain.

The management strategy evaluation (MSE) approach has been applied to several fisheries around the world (e.g. Punt, 1992; De la Mare, 1996; Butterworth et al., 1997; Punt and Smith, 1999; Smith et al., 1999; Punt et al., 2002a,b,c). The major benefit of the MSE approach is that the effects of different management strategies can be evaluated by managing a "virtual" resource. The resource is represented using an "operating model", and future management actions are based on a management strategy (usually, but not always, the combination of a data collection scheme, a method of stock assessment, and a decision rule that converts the results of the assessment into specifications for management actions—such as levels of fishing effort). The operating model therefore represents the "truth" for the evaluations.

Dichmont et al. (2006a,b) apply the MSE approach to the NPF. The analyses are based on a two-species, 5-stock operating model, and examine the performance of some possible management strategies for the NPF tiger prawns, and specifically how assumptions made regarding spatial structure impact performance. Banana prawns are not modelled explicitly, but their impact on the management system is simulated empirically. This latter approach is reasonable as there is no stock assessment for banana prawns and no evidence that the catches of banana and tiger prawns are correlated. Three "assessment procedures" are considered (simple catch-rate regression, biomass dynamic and delay-difference models) and two types of management action (setting the total fishing effort and setting the season start and end dates). The performance of the management strategies is evaluated in terms of whether stocks are left at (or above) the spawning stock size at which maximum sustainable yield is achieved (S_{MSY}), the long-term discounted total catch, and the extent of inter-annual variation in catches.

This paper examines the performance of management strategies (as opposed to the assessments themselves) for the NPF tiger prawns to determine which factors impact performance to the greatest extent. Attempts to resolve these uncertainties could be the focus of future research. Overall therefore, Dichmont et al. (2006a,b) and the present paper provide the basis for developing management strategies that are robust to the key uncertainties that have been identified to date for tiger prawns in the NPF.

2. Methods

2.1. Performance measures

There are two types of performance measures in the context of an MSE: (a) management-related performance measures and (b) estimation-related performance measures. Management-related performance measures relate to the ability of a management strategy to satisfy (to the extent possible) the management objectives for the fishery, while estimation-related performance measures quantify how well stock assessment methods are able to estimate quantities that are of interest to the decision makers (such as MSY, E_{MSY}, and current spawning stock biomass). It should be noted that management-related performance measures are obtained only from the operating model (i.e. the "truth") rather from the assessment procedure in the management strategy (i.e. the perception of truth based on assessment model settings and data). In common with previous MSE exercises in Australia (e.g. Polacheck et al., 1999; Punt et al., 2001a,b; Campbell and Dowling, 2003), this paper focuses on management-related performance measures related to the sustainability of the stocks and of the fishery.

2.1.1. Conservation-related performance measures

Unfortunately, prior to 2001, NPF-specific management goals were incompletely articulated as "set the fishing effort to that corresponding to MSY" and thereafter were revised to relate to recovering the spawning stock size to the level at which, in expectation, MSY is achieved (S_{MSY}). The conservation-related performance measures considered in this study are therefore based primarily on the size of the spawning stock relative to S_{MSY} (which is now treated as a limit reference point, i.e. success is defined as leaving the spawning stock size above S_{MSY}) although other 'biological bottom lines', $0.2S_{\mathrm{VIR}}$ (20% of the pre-fishery or virgin spawning stock size) and S_{low} (the lowest spawning stock size encountered to date) are also considered. Note that there is no evidence that depleting a resource to below S_{MSY}, $0.2S_{\mathrm{VIR}}$ or S_{low} will necessarily lead to severe biological problems. Nevertheless, these measures are still useful to define the (relative) risk to the resource due to exploitation. In the results, we present the probability that the spawning stock size in 2010 has fallen below these reference points (e.g. $P(S_{2010}/S_{\mathrm{MSY}})$), as well as the actual ratio of, for example, $S_{2010}/S_{\mathrm{MSY}}$.

2.1.2. Economic-related performance measures

There are two approaches to developing performance measures that capture the economic aspects of the outcomes of the use of a management strategy. The first is to develop a model that explicitly considers fleet dynamics and the costs of harvesting, and can determine the profitability of the fishery for different management strategies. The second, which forms the basis for this paper, is to assess economic performance using simple proxies. The four proxies used for the economic performance of the management strategies are:

(a) Total discounted annual total catch, i.e.:

$$C^{\mathrm{T}} = \sum_{y} C_y \, \mathrm{e}^{-\delta(y-2003)} \tag{1}$$

where C_y is the catch (aggregated over prawn species, weeks, and areas) during year y; and δ is the economic discount rate (assumed to be 5% for the analyses of this paper).

(b) Percentage of years that the catch is less than some critical level, C_{crit}, $P(C_y < C_{\mathrm{crit}})$; the value of C_{crit} is taken to be 2000t, a level below which the profits to the industry are likely to be negative (T. Kompas, Australian National University, personnel communication).

(c) C_{low}, the lowest catch taken over the period 2003–2015. The median and the lower 5th percentile of the discounted total catch across simulations are reported.
(d) Stability of catches. The stability of the catches is measured by the average absolute (percentage) change in landed catches from year to year, AAV:

$$\text{AAV} = \frac{100\sum_{y=2003}^{2015}|C_y - C_{y-1}|\,e^{-\delta(y-2003)}}{\sum_{y=2003}^{2015}C_y\,e^{-\delta(y-2003)}} \tag{2}$$

Eq. (2) is based on the total catch of all tiger prawn species over all weeks and areas. This equation implicitly assumes that the value of the catch is independent of week, area, and species. In principle, allowance could be made for week-, species- and area-specific prices and costs, but such an evaluation is beyond the scope of the present study.

2.2. Factors affecting performance measures

A completely balanced test of all factors to identify which are most influential on the performance measures would have been computationally infeasible, and in a practical sense unnecessary. A two-stage process was therefore used to, firstly, identify which factors (singly or combined with others, both in terms of specifications for the operating model and those for the management strategies) significantly affect the performance measures, and secondly, to investigate in detail what this affect is in terms of trend and degree. Viewed as an experimental design, the set for the first test is unbalanced, but is nevertheless able to permit the identification of the key factors. The second part uses a balanced test of the significant factors.

The management strategies are based on three "assessment procedures" (the Deriso delay-difference model that forms the basis for current assessments of the resources, a biomass dynamics model, and a simple linear regression-based empirical method—see Dichmont et al. (2006b) for additional details). Table 1 lists the factors (apart from "assessment procedure") considered in the experiment and the levels for each factor. The factors in Table 1 include the six sources of error and uncertainty that can be incorporated into a risk assessment identified by Francis and Shotton (1997). Four of these sources (process uncertainty, observation uncertainty, model uncertainty and implementation uncertainty) pertain to the operating model and the other two (estimation and error structure uncertainty) pertain to fitting models to data. Note that not all combinations of factor levels can be chosen to create a scenario. For example, the "simple regression" approach only uses catch-rate data and so does not make an assumption regarding changes over time in fishing efficiency.

The medians of the performance measures for each scenario are analysed by species and "assessment procedure". The following process is used to analyse the each performance measure:

(1) a linear model with all possible main effects is fit;
(2) the most parsimonious main effects model is selected according to the 'Bayesian Information Criterion' (BIC);
(3) the most complete possible main and second-order effects model is fit using an ANOVA; and
(4) the most parsimonious final model is selected using the BIC based on this second-order model, but the BIC itself uses the estimate of variance computed from by the most parsimonious main effects model chosen at step 2. This process ensures a reasonable variance estimate is used and avoids the problems of using a variance estimate from an over-fitted linear model.

Table 1
Description of the factors (other than assessment procedure) examined in main experiment, their abbreviations, and the levels for each factor (in parenthesis)

Abbreviation	Description
Factors relevant to the operating model	
FpOp	True scenario regarding changes over time in efficiency (Base Case High, BCH; Base Case Low, BCL)
qOp	The catchability coefficient in the operating model (q from Wang (1999)—"q"; twice the value of q from Wang (1999)—"2q")
OE	Coefficient of variation of observation error on catch (CV = 0; CV = 10%)
SCR	Is recruitment spatially correlated? (no; based on the historical correlations of the residuals about the fit of the stock–recruitment relationship for each area and species)
DE	Coefficient of variation of the extent of implementation error (CV = 0; CV = 15%; CV = 30%)
Rval	Method for selecting parameter vectors (generated from the variance–covariance matrix; generated from a Bayesian posterior distribution)
PSeason	Is the season length changed annually? (yes; 1 chance in 3)
PEffort	Is the effort level changed annually? (yes; 1 chance in 3)
Factors relevant to the management strategies	
FpAss[B,C]	Assumed scenario regarding changes over time in efficiency (Base Case High, BCH; Base Case Low, BCL)
qAss[B,C]	The catchability coefficient in the assessment model (q from Wang (1999)—"q"; twice the value of q from Wang (1999)—"2q")
CWt[D]	Area allocation weight to past cpue (1; 1.5)
RefPt[C]	The fractions of S_{MSY} and E_{MSY} used when determining target effort (1/1; 1.2/0.8)
RefYear[B,C]	The range of years used when determining E_{MSY} (1993–2002; most-recent 10 years)

Factors superscripted by "B", "C" and "D" are not relevant to the biomass dynamics model, cpue regression approach, and Deriso management strategies, respectively. Full descriptions how the factors related to management strategies are implemented are given by Dichmont et al. (2006b).

The conservation-related performance measures are calculated for each year, but are only analysed and presented for 2010. Since these performance measures are proportions, they are transformed by arcsin($\sqrt{p}$) to obtain a response variable for which the residual variance about the regression is independent of the estimate. Since the conservation-related performance measures relate to the "true" resource being managed, there are conservation-related performance measures for each of the eight species × stock combinations. In addition, the spawning stock sizes can be added together and NPF-wide conservation-related performance measures produced. However, little is gained by analysing the performance measures for each stock area individually or by excluding some of the stock areas. The analyses therefore focus on performance measures aggregated over stock areas (i.e. NPF-wide) by species. The analyses of the economic-related performance measures that were not proportions were based on log-transformed values.

The second stage of determining the sensitivity of the performance measures to the various factors involves investigating the effects of each of the key factors using a series of balanced simulation experiments. The most appropriate method to illustrate these effects is graphical (rather than numerical) because graphs can highlight the size of effects, and permits simple visual appreciation of any trends.

3. Results and discussion

3.1. Identifying factors that affect performance measures: an unbalanced design

Fig. 1 summarizes all of the conservation-related performance measures (aggregated over all of the simulations on which the unbalanced experiment (Table 1) is based). There is generally a very small probability of the spawning stock size in 2010 being below the lowest spawning stock size encountered historically and a small probability of the spawning stock size in 2010 being below 20% of the pre-exploitation spawning stock size. The remaining analyses of this paper therefore focus on the performance measure $P(S_{2010} > S_{\mathrm{MSY}})$ (by species) because it is more discriminating.

Tables 2 and 3 provide a summary of the factors that are highly significant ($P < 0.05$) in the linear model fits to $P(S_{2010} > S_{\mathrm{MSY}})$ and the four economic-related performance measures. Table 2 demonstrates that assumptions regarding fishing power, catchability, whether recruitment is correlated spatially among stocks, the extent of implementation error, and the target spawning stock size used in the decision rule, have the largest impact on the values of the conservation-related performance measures. In contrast, more of the factors appear to influence the values of the economic-related performance measures (Table 3), and there are quite noteworthy differences in which factors are most influential among the four economic performance measures. In addition to all of the factors that are highly significant for $P(S_{2010} > S_{\mathrm{MSY}})$, how the parameter vectors used to represent parameter uncertainty in the operating model are generated, as well as some of the interactions between the fishing power assumed when conducting Deriso-model-based assessments and other factors are also highly significant factors determining the values for the economic-related performance measures.

3.2. Key factors that affect performance measures: balanced design

The key factors affecting performance identified in the unbalanced experiment were: (1) fishing power; (2) catchability; and (3) fishing power and catchability combined, while the factors of lesser importance were: (4) the extent of implementation error; (5) whether recruitment is correlated spatially among stocks or not; and (6) the method used to capture parameter uncertainty. As a result, the key factors determining the per-

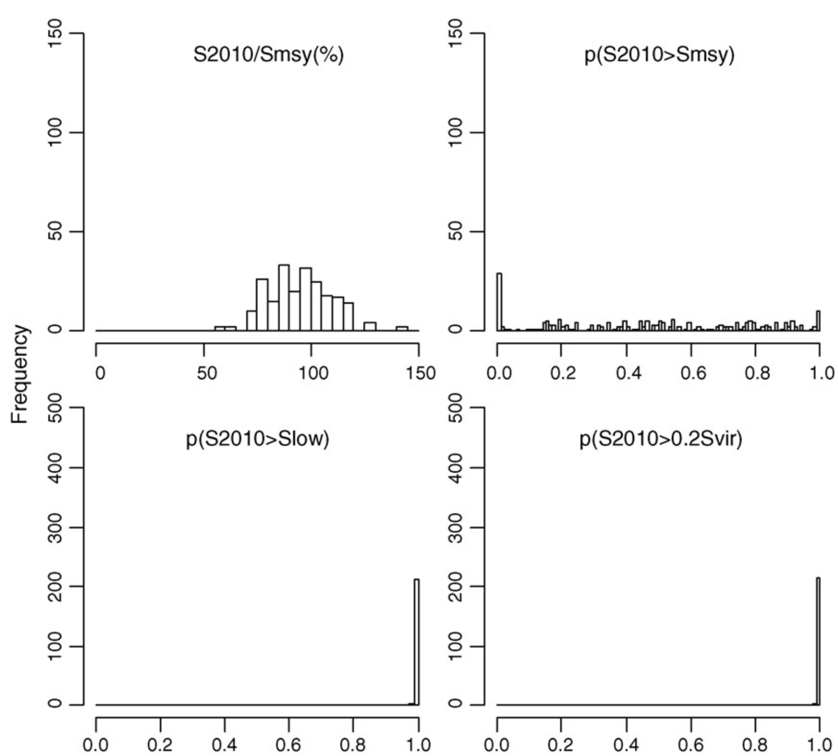

Fig. 1. Frequency distributions of the NPF-wide conservation-related performance measures across all scenarios for the unbalanced experiment. Figure (clockwise from upper left) are the spawning stock size in 2010 expressed as a percentage of the spawning stock size at which MSY is achieved, the probability that S_{2010} is greater than S_{MSY}, the probability of S_{2010} is higher than S_{low}, and the probability that S_{2010} is higher than $0.2S_{\mathrm{VIR}}$.

Table 2
Summary of the regression results for the management-related performance measure $P(S_{2010} > S_{\mathrm{MSY}})$ (PS = *P. semisulcatus*, PE = *P. esculentus*)

Factor	PS Deriso	PE Deriso	PS biomass dynamic	PE biomass dynamic	PS cpue regression	PE cpue regression
FpOP	√	√				
FpASS	√	√	n/a	n/a	n/a	n/a
DE	√				√	√
SCR	√	√	√	√	√	√
qOp	√	√				
qAss	√		n/a	n/a	n/a	n/a
Rval	√		√		√	
RefPt	√	√	√	√		
RefYear	√		n/a	n/a	n/a	n/a
FpOP:FpASS	√		n/a	n/a	n/a	n/a
FpASS:DE	√		n/a	n/a	n/a	n/a
FpASS:SCR	√	√	n/a	n/a	n/a	n/a
FpASS:qOp	√		n/a	n/a	n/a	n/a
FpAss:qAss	√		n/a	n/a	n/a	n/a
FpAss:Rval	√		n/a	n/a	n/a	n/a
FpAss:RefYear	√		n/a	n/a	n/a	n/a
FpOp:qOp		√				
DE:qOp	√					
SCR:DE			√	√	√	√

The checked factors (see Table 1 for details) are significant at the 5% level and are included in the final model. 'n/a' means not applicable. The factors that were considered but found to be not significant are ignored for this table.

formance measures fall within the categories of process error (#5), implementation uncertainty (#4), and model uncertainty (#s 1, 2, 3 and 6). Observation error does not turn out to be a major source of uncertainty, although some authors consider uncertainty about fishing power a source of observation error (e.g. Punt and Butterworth, 1999). The following sections explore the impact of each of these six factors using a balanced set of simulation trials. Factorial experimental designs are rarely used in simulation studies, but see also Kell et al. (1999).

3.2.1. Fishing power

There is considerable uncertainty regarding the extent to which fishing power in the NPF has changed over time (Wang and Die, 1996; Haddon, 1997, 2001; Dichmont et al., 2003b). Furthermore, assumptions regarding changes over time in fishing power can have substantial impacts on the results of stock assessments of tiger prawns (Dichmont et al., 2001, 2003a). It is therefore not surprising that the performance measures from the MSE are also very sensitive to which of the two fishing power series considered (BCH and BCL) is correct.

Table 3
Summary of the final models for the economic-related performance measures

Factor	Total discounted catch			AAV			C_{low}			$P(C_y < 2000t)$		
	D	C	B	D	C	B	D	C	B	D	C	B
FpOP	√						√					
FpASS	√	n/a	n/a	√	n/a	n/a	√	n/a	n/a		n/a	n/a
qOP	√						√					
Rval	√	√	√					√	√	√	√	√
RefPt	√		√			√			√			
FpOP:FpASS	√	n/a	n/a		n/a	n/a		n/a	n/a		n/a	n/a
FpOP:qOP	√						√					
FpOP:RefPt	√	n/a	n/a		n/a	n/a		n/a	n/a		n/a	n/a
FpASS:RefPt	√	n/a	n/a		n/a	n/a		n/a	n/a		n/a	n/a
FpASS:DE		n/a	n/a	√	n/a	n/a		n/a	n/a		n/a	n/a
SCR		√	√	√	√	√		√	√			√
DE		√		√	√	√	√	√	√	√	√	√
SCR:DE		√		√	√	√		√				
SCR:qAss		n/a	n/a	√	n/a	n/a		n/a	n/a		n/a	n/a
OE			√			√			√			
OE:SCR			√									
qAss		n/a	n/a	√	n/a	n/a		n/a	n/a		n/a	n/a
PEffort						√						

Checked factors (see Table 1 for details) are significant at the 5% level and are included in the final models. "n/a" indicates "not applicable", "D", "C" and "B" denote the "Deriso", "cpue regression" and "biomass dynamics" management strategies, respectively. The factors that were considered but found to be not significant are ignored for this table.

Table 4
Settings and performance measures (medians with 90% intervals in parenthesis)

Acronym	Operating model (fishing power, catchability)	Management strategy (fishing power, catchability)	$P(S_{2010} > S_{MSY})$		S_{2010}/S_{MSY} PS (%)	S_{2010}/S_{MSY} PE (%)	Total discounted catch (‘000t)	AAV	C_{low} (‘000t)
			PS	PE					
(a) Varying the fishing power in the operating model and the assessment									
D – BC	H, q	H, q	0.67	0.16	99.9 (78.8–127.6)	79.8 (58.1–104.4)	25.5 (22.8–28.7)	12.9 (9.2–18.3)	1.9 (1.7–2.3)
D – L_op L_ms	L, q	L, q	0.82	0.30	109.6 (87.1–136.6)	87.2 (64.1–112.2)	27.2 (24.2–30.7)	15.2 (11.1–20.3)	1.9 (1.6–2.3)
D – H-q_op L-q_ms	H, q	L, q	0.14	0.20	82.3 (65.3–107.7)	63.4 (44.5–87.8)	26.0 (23.1–29.4)	16.1 (12.1–22.2)	1.9 (1.6–2.2)
D – L-q_op H-q_ms	L, q	H, q	0.99	0.62	126.6 (102.4–158.3)	104.5 (79.6–132)	25.1 (22.2–28.2)	13.1 (8.8–17.8)	1.9 (1.7–2.2)
(b) Varying the catchability coefficient in the operating model and the assessment									
D – BC	H, q	H, q	0.67	0.16	99.9 (78.8–127.6)	79.8 (58.1–104.4)	25.5 (22.8–28.7)	12.9 (9.2–18.3)	1.9 (1.7–2.3)
D – 2q_op 2q_ms	H, 2q	H, 2q	0.83	0.17	108.8 (87.4–136.6)	82.5 (60.6–109.8)	25.4 (22.6–28.3)	12.2 (7.9–17.3)	2.0 (1.7–2.3)
D – 2q_ms	H, q	H, 2q	0.69	0.23	102.2 (81.0–130.7)	84.7 (62.1–108.5)	25.3 (22.8–28.5)	12.6 (8.1–17.0)	1.9 (1.7–2.3)
D – 2q_op	H, 2q	H, q	0.78	0.11	106.3 (85.2–132.9)	79.0 (57.8–105.1)	25.4 (22.6–28.3)	12.7 (8.6–17.1)	2.0 (1.6–2.3)
(c) The biomass dynamic model (“B”) and cpue regression method (“C”) management strategies									
B – BC	H, q	n/a, n/a	0.68	0.20	102.7 (80.6–128.2)	82.4 (56.6–105.8)	24.9 (22.4–27.5)	17.3 (11.2–43.7)	1.9 (0.8–2.2)
B – 2q_op	H, 2q	n/a, n/a	0.89	0.36	112.8 (93.6–141.4)	89.8 (63.5–116.2)	27.2 (24.8–29.3)	15.1 (9.5–23.4)	2.1 (1.6–2.4)
C – BC	H, q	n/a, n/a	0.92	0.47	115.5 (94.2–147.7)	94.6 (69.4–120.0)	24.1 (21.9–26.7)	10.4 (6.2–15.2)	1.9 (1.7–2.2)
C – 2q_op	H, 2q	n/a, n/a	0.97	0.57	121.3 (100.4–149.9)	98.8 (72.0–126.4)	26.8 (24.5–29.0)	9.9 (5.8–15.1)	2.3 (2.0–2.5)
(d) The extent of implementation error									
D – BC	H, q	H, q	0.67	0.16	99.9 (78.8–127.6)	79.8 (58.1–104.4)	25.5 (22.8–28.7)	12.9 (9.2–18.3)	1.9 (1.7–2.3)
D – 15% DE[a]	H, q	H, q	0.44	0.15	92.3 (74.1–127.8)	76.9 (55.0–106.9)	25.2 (22.4–29.1)	16.7 (10.6–24.9)	1.8 (1.5–2.3)
D – 30% DE[b]	H, q	H, q	0.44	0.14	92.9 (72.5–129.7)	77.5 (53.6–106.0)	25.0 (22.1–29.2)	24.9 (14.9–34.9)	1.6 (1.1–2.1)
(e) Spatial auto-correlation in recruitment success									
B – BC	H, q	n/a, n/a	0.68	0.20	102.7 (80.6–128.2)	82.4 (56.6–105.8)	24.9 (22.4–27.5)	17.3 (11.2–43.7)	1.9 (0.8–2.2)
B – with correlation[c]	H, q	n/a, n/a	0.58	0.0	96.4 (89.9–99.2)	71.5 (63.0–76.7)	24.3 (23.0–25.1)	14 (107–44.4)	1.9 (0.4–2.1)
C – BC	H, q	n/a, n/a	0.92	0.47	115.5 (94.2–147.7)	94.6 (69.4–120.0)	24.1 (21.9–26.7)	10.4 (6.2–15.2)	1.9 (1.7–2.2)
C – with correlation[c]	H, q	n/a, n/a	1.00	0.0	111.2 (108.0–114.1)	85.7 (81.3–90.1)	23.0 (22.0–24.0)	4.3 (2.8–6.4)	2.0 (1.7–2.1)
D – BC	H, q	H, q	0.67	0.16	99.9 (78.8–127.6)	79.8 (58.1–104.4)	25.5 (22.9–28.7)	12.9 (9.2–18.3)	1.9 (1.7–2.3)
D – with correlation[c]	H, q	H, q	0.52	0.0	96.2 (92.3–99.4)	73.5 (70.2–78.0)	24.3 (23.2–25.1)	7.6 (5.8–10.2)	2.0 (1.8–2.2)

PS is *P. semisulcatus*, PE is *P. esculentus*.
[a] Includes an implementation error CV of 15%.
[b] Includes an implementation error CV of 30%.
[c] Includes spatially correlated recruitment.

Table 4(a) explores the effects of assumptions regarding changes over time in fishing power on the performance measures for two management strategies and two operating models based on the "Deriso" management strategy and the Base Case operating model:

- "D – BC"—both the operating model and the management strategy are based on BCH;
- "D – L_op L_ms"—both the operating model and the management strategy are based on BCL;
- "D – H-q_op L-q_ms"—the operating model is based on BCH and the management strategy on BCL; and
- "D – L-q_op H-q_ms"—the operating model is based on BCL and the management strategy on BCH.

As expected, the largest effects occur when the fishing power series underlying the operating model differs from that underlying the management strategy. The spawning stock size is above S_{MSY} (substantially so for *P. semisulcatus*) when the management strategy is based on BCH, but "reality" is BCL ("D – L-q_op H-q_ms" in Table 4(a)) and is below S_{MSY} (substantially so for *P. esculentus*) when the management strategy is based on BCL, but "reality" is BCH ("D – H-q_op L-q_ms" in Table 4(a)). Somewhat surprisingly, the lowest catches and the total discounted catches for "D – H-q_op L-q_ms" and "D – L-q_op H-q_ms" are fairly similar, although this result should be interpreted with some caution because changing the fishing power scenario in the operating model also changes the current status and productivity of the "true" population.

The MSE can be used to explore the impact of assumptions regarding changes over time in fishing power on estimation ability. As expected, the estimates of key model outputs are relatively unbiased when the assessment is based on the correct fishing power scenario, but substantial biases occur when this is not the case. For example, the estimate of E_{MSY} is positively biased when the assessment is based on BCL, but reality is BCH and the estimates of steepness and E_{MSY} are negatively biased and those of S_{MSY} positively biased when the assessment is based on BCH, but reality is BCL. This suggests that estimation bias is a key reason for the differences in performance that occur when the assumed fishing power series differs from the true fishing power series.

3.2.2. Catchability

The value assumed for the catchability coefficient during 1993, $\tilde{q}$, has a substantial influence on the results of the Deriso model-based assessment of tiger prawns in the NPF (Dichmont et al., 2003a). The estimate of $\tilde{q}$ obtained by Wang (1999) may be negatively biased because its calculation is based on the assumption that there is no recruitment during October when, in fact, recruitment is expected to be increasing (Somers, 1990; Somers and Wang, 1997; Wang and Die, 1996). Current practice when developing scientific management advice is therefore to conduct assessments for the value of $\tilde{q}$ obtained by Wang (1999) and twice this value (the "q" and "2q" scenarios).

Table 4(b) explores the effects of assumptions regarding $\tilde{q}$ on the performance measures for two management strategies and two operating models based on the "Deriso" management strategy and the Base Case operating model:

- "D – BC"—both the operating model and the management strategy are based on "q";
- "D – 2q_op 2q_ms"—both the operating model and the management strategy are based on "2q";
- "D – 2q_ms"—the operating model is based on "q" and the management strategy on "2q"; and
- "D – 2q_op"—the operating model is based on "2q" and the management strategy on "q".

The management-related performance measures are less sensitive to assumptions regarding $\tilde{q}$ than to assumptions regarding fishing power. Also, these performance measures are more sensitive to assumptions regarding how $\tilde{q}$ is treated in the assessment than to how it is treated in the operating model. How $\tilde{q}$ is treated in the assessment also impacts estimation ability. For example, and as expected, the estimates are more conservative when the assessment procedure is based on "2q" rather than on "q".

3.2.3. Biomass dynamic and cpue regression

In contrast to the management strategies based on the Deriso model, the management strategies based on the biomass dynamic model and on the cpue regression approach are sensitive (the latter less so) to the true value of $\tilde{q}$ in the operating model (Table 4c). Catchability is estimated within the assessment based on the biomass dynamic model. However, the estimate is about an order of a magnitude smaller than the true value, and there is no large increase in the estimate of catchability from the biomass dynamic model when catchability in the operating model is "2q". Therefore, although it would be ideal to estimate catchability within the assessment, there seems little ability to do so given the available data.

3.2.4. Fishing power and catchability

This section explores the impact of the interaction between the value for $\tilde{q}$ and the fishing power series in the operating model and the value for $\tilde{q}$ and the fishing power series in the assessment. An investigation of all 16 possible combinations of these two factors is undertaken for management strategies based on the Deriso model.

The effectiveness of a management strategy at leaving the spawning stock size at (or above) S_{MSY} is influenced substantially by the combination of catchability and fishing power selected when conducting the assessment and how this relates to catchability and fishing power assumed in the operating model. There are trade-offs between the size of the spawning stock size for each species and the discounted catch taken from the fishery. An efficient way of illustrating these trade-offs, given the number of possible combinations, is to plot the median $S_{2010}/S_{\mathrm{MSY}}$ (%) against the median discounted catch for each management strategy (Fig. 2). Results are grouped by operating model in Fig. 2.

It should be noted that the results in Fig. 2 range from the assessment model being based on the correct assumptions about catchability and fishing power to it being based on completely

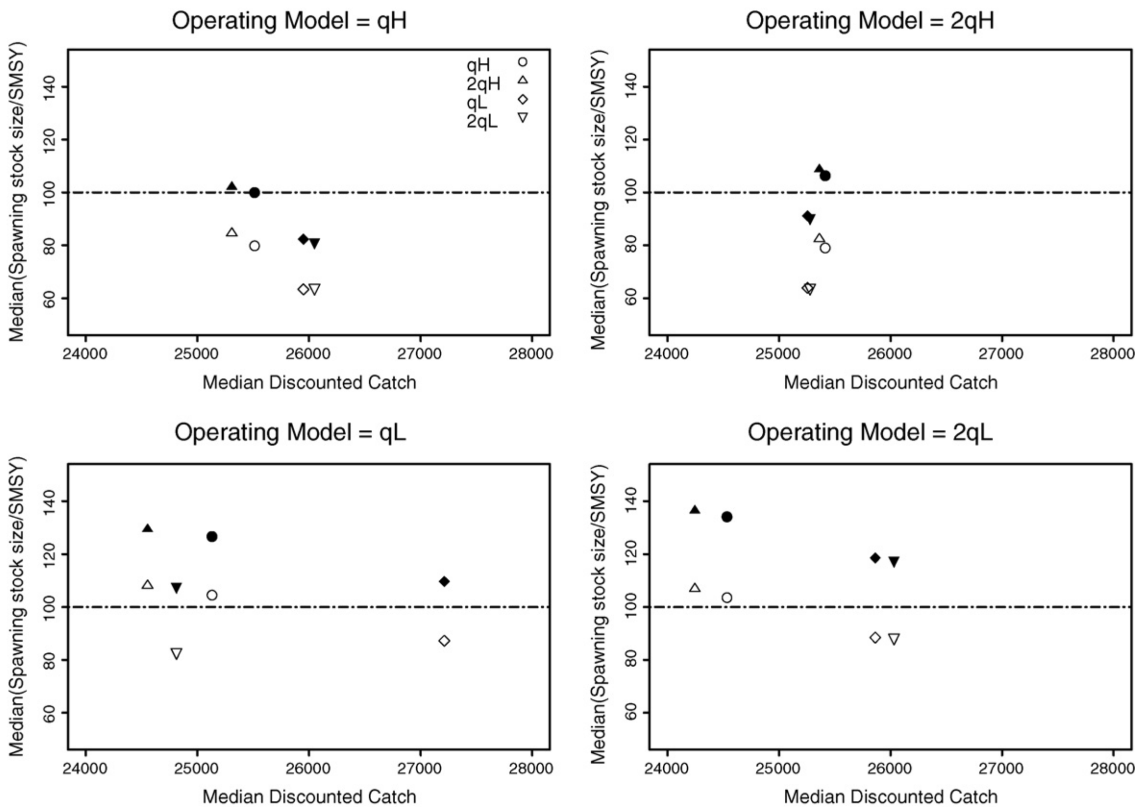

Fig. 2. Median values for $S_{2010}/S_{\mathrm{MSY}}$ vs. median discounted catches for four management strategies based on the Deriso model-based assessment procedure for each of four operating models. The specifications for the operating models/management strategies depend on the value for $\tilde{q}$ ("q" and "2q") and the fishing power series (Base Case High "H" and Base Case Low "L"). The results for *P. semisulcatus* are indicated by the solid symbols and those for *P. esculentus* by the open symbols.

incorrect assumptions. The ideal management strategy would perform best for all of the operating models.

A few general patterns emerge (Fig. 2):

(1) There is a trade-off between the status of the resource in 2010 and the total catch; this trade-off is most obvious for the "2qL", "qL" and "qH" operating models.
(2) Basing the assessment model on a catchability value of "2q" and the "Base Case High" fishing power series (triangles in Fig. 2) leads to the most conservative performance in terms of $S_{2010}/S_{\mathrm{MSY}}$, irrespective of the settings in the operating model.
(3) The "2qH" and "qH" management strategies (triangles and circles in Fig. 2) are the "best" options in terms of trade-offs for the operating model "2qH"—they lead to higher median discounted catches and higher spawning stock sizes in 2010 than the "qL" or "2qL" management strategies (i.e. these latter two management strategies are "dominated" by the "2qH" management strategy for this operating model).

Given that all of the management strategies that were based on the Deriso assessment procedure tend to leave the spawning stock size of *P. esculentus* below the target level of S_{MSY} in median terms, it would appear to be more precautionary to select conservative assessment model settings until a management strategy is developed that is better able to leave the spawning stock size of *P. esculentus* above S_{MSY}. Assuming the Base Case High fishing power series when conducting assessments leads to a higher probability of leaving the spawning stock size at (or above) S_{MSY} for both tiger prawn species (Fig. 2). Of the management strategies based on the "Base Case High" fishing power series, that based on setting $\tilde{q}$ to "q" is more conservative than that based on setting $\tilde{q}$ to "2q", although the difference is slight, at least compared to the impact of the choice of the fishing power series.

Fig. 3 explores estimation performance for the four management strategies by plotting the median relative errors of the estimates of $S_{2005}/S_{\mathrm{MSY}}$ against those of S_{MSY}. Setting $\tilde{q}$ to "q" and assuming the Base Case High fishing power series (circles in Fig. 3) leads to the highest estimates of S_{MSY} while setting $\tilde{q}$ to "2q" and assuming the Base Case Low fishing power series (downward triangles in Fig. 3) leads to the lowest estimates of S_{MSY}. In contrast, the most positively biased estimates of $S_{2005}/S_{\mathrm{MSY}}$ occur when the Base Case Low fishing power series is assumed when conducting the assessment while assuming the Base Case High fishing power series when conducting assessments leads to the most negatively biased estimates of $S_{2005}/S_{\mathrm{MSY}}$.

3.2.5. Implementation error

Implementation error relates to the difference between the actual fishing effort expended in the fishery and that intended from the outcomes of the management strategy (Dichmont et al., 2006a). Dichmont et al. (2006a) estimate that the coefficient

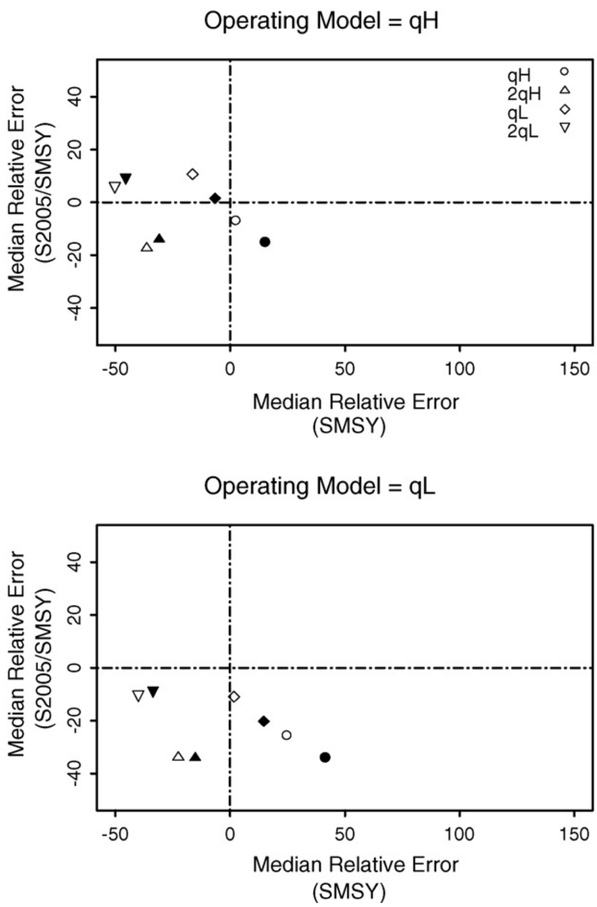

Fig. 3. Median relative errors for S_{2005}/S_{MSY} and S_{MSY} when the Deriso model-based assessment procedure is applied in 2010. Results are shown for four variants of the assessment procedure and for four operating models. The specifications for the operating models/management strategies depend on the value for $\tilde{q}$ ("q" and "2q") and the fishing power series (Base Case High "H" and Base Case Low "L"). The results for *P. semisulcatus* are indicated by the solid symbols and those for *P. esculentus* by the open symbols.

of variation of the amount of implementation error in the NPF tiger prawn fishery is 18% on average, but implementation error could be as high as 30% in some years. Note that implementation error is assumed to relate only to the total amount of fishing effort because it is assumed that VMS makes it possible to ensure that the length of the season (including the mid-season closure) is implemented exactly.

Table 4(d) contrasts the values for the management-related performance measures from management strategies based on the Deriso model assessment procedure with three scenarios regarding the extent of implementation error (0, 15 and 30%). There is relatively little impact of different levels of implementation error on the management-related performance measures based on S_{2010}/S_{MSY} and total discounted catch (Table 4d). In contrast, implementation error has a marked impact on the values for some of the economic-related performance measures. Specifically, larger amounts of implementation error lead to higher inter-annual variation in catches (AAV), and a lower lowest catch (C_{low}). These results are perhaps not unexpected because there is no "bias" caused by implementation error; rather the average fishing effort level will be imposed as anticipated, but with larger inter-annual variation for larger amounts of implementation error.

3.2.6. Spatial correlation in recruitment among stocks

The Base Case operating model only includes within-stock temporal (i.e. inter-annual) correlation in recruitment (Dichmont et al., 2006a). This implies that each stock acts totally independently of all other stocks, and that recruitment during 1 year is only affected by the previous year's spawning stock size and the environment within the area in which the stock is found. However, it is possible that a (currently unidentified) environmental variable affects recruitment success over a much larger area than a single stock area. The extent of inter-stock correlation in the deviations about the stock–recruitment relationship was estimated based on the fit of the operating model to the data, and this was then used when generating future recruitment. This approach to allowing for spatial correlation in recruitment assumes that the environmental variable(s) that affected the spatial correlation in recruitment in the past will do so in the future.

The probability of being above S_{MSY} for both tiger prawn species is reduced when allowance is made for spatial correlation in recruitment (Table 4e). The estimation performance of the Deriso model assessment procedure is generally not affected substantially by allowing for spatial correlation in recruitment. However, unlike the case for the Base Case operating model, there is evidence for positive bias in the estimates of S_y/S_{MSY}

for *P. esculentus* from 2006 when there is spatial correlation in recruitment.

Studies of the effects of environmental factors such as temperature and rainfall on recruitment have been undertaken over decades with mixed success (e.g. Francis et al., 1989; Sparholt, 1996). In this study, the mechanism that impacts recruitment over large spatial scales is not known, but rather the environment is included as a generic inter-annual auto-correlation matrix based on that observed in the available data. Many studies consider that robust management strategies should be developed in spite of this source of uncertainty (e.g. Walters and Collie, 1989) rather than place emphasis on detailed studies of direct statistical correlations and mechanisms (e.g. Parker, 1989; Laevastu, 1992; Ulltang, 1996).

3.3. General discussion

It is clear that, for the management strategies based on the Deriso model-based assessment procedure, how the 1993 catchability coefficient is determined and fishing power values chosen are important factors that influence the ability to satisfy the management objectives. Not unexpectedly, the target spawning stock size used in the decision rule is also important; problems with the MSE system would have been flagged if this was not the case. It is perhaps surprising that whether recruitment is correlated spatially or not had an important impact on the results. This implies that any future work on stock boundaries and stock-specific assessments should consider this issue and attempts should perhaps be made to gain some understanding of the underlying mechanisms.

The ideal when managing a fishery is to apply an unbiased and precise stock assessment method and to implement a management system that achieves the management objectives. However, if this ideal cannot be achieved, it is better to use a biased stock assessment procedure with a management system that achieves the management objectives, rather than an unbiased stock assessment procedure and a management system that does not. Finally, given that the management strategies based on the Deriso assessment procedure tend to leave the spawning stock size of *P. esculentus* below the target level of S_{MSY} in median terms, a case could be made for choosing one of the more conservative management strategies, at least until a management strategy is identified that performs better for *P. esculentus*.

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