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Management strategies for short lived species: The case of Australia's Northern Prawn Fishery 2. Choosing appropriate management strategies using input controls

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Abstract

A Management Strategy Evaluation framework is used to evaluate management strategies based on input controls for the fishery for two tiger prawn species (*Penaeus esculentus* and *Penaeus semisulcatus*) in Australia's Northern Prawn Fishery. Three "assessment procedures" are considered and two forms of decision rule. 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. The focus of the analysis is on management strategies based on the current method of stock assessment because an alternative method of assessment based on a biomass dynamics model is found to be highly variable. None of the management strategies tested is able to leave the spawning stock size of *P. esculentus* near S_{MSY} if the target effort level used in the management strategy is set to E_{MSY}. Accounting for stock structure through the application of a spatially- (stock-) structured assessment approach fails to resolve this problem. Since the assessment method is generally close to unbiased, the failure to leave the stocks close to S_{MSY} is because the measure of control is total effort and the two species are found (and caught) together. Reducing the target effort level to below E_{MSY} increases the final stock size, but the reduced risk comes at a cost of reduced catches. The best management strategy in terms of leaving both species close to S_{MSY} is found to be one that changes the timing of the fishing season so that effort is shifted from *P. esculentus* to *P. semisulcatus* and sets more precautionary effort targets for *P. esculentus*.

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

1. Introduction

Australia's Northern Prawn Fishery (NPF) started mainly as a banana prawn (*Penaeus merguiensis*) fishery in the 1960s, but expanded over time to be a multi-species prawn fishery with tiger prawns (brown and grooved tiger prawns; *Penaeus esculentus* and *Penaeus semisulcatus*) as the most valuable component of the catch (Pownall, 1994). Initially, the vessels in the fishery were small wooden quad-rigged otter trawlers with brine storage tanks. In contrast, the vessels in use today are large steel specialized prawn trawlers with computers, GPS and plotters that use spotter planes during the banana prawn season. The fleet now lands between 6000 and 8000 tonnes of prawns annually from the NPF. Over the period 1992/1993 to 2001/2002, real revenue for operators fluctuated between AU$ 115.8 and AU$ 185.7 million, with an average of AU$ 146.8 million (2002–2003 dollars) (Galeano et al., 2004), making the NPF one of Australia's most valuable fisheries.

Input controls (attempts to manage effort) rather than output controls (e.g. catch quotas) have formed the basis for management of the NPF. Changes to an allocated effort unit (similar in concept to a tradeable quota) and season length are used to implement changes in effort. Management of the NPF since the 1980s has been characterized by attempts to restructure the fishery and reduce effort. This was driven by the substantial increases in fishing mortality as new technologies were adopted. Approaches to

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Table 1
History of management decisions relating to target species control within the NPF

Year	Scientific advice and management development
1980	Introduction of limited entry
1985	Statutory Fishery Rights granted in the form of A-units. Voluntary buyback scheme introduced which tended to reduce only latent effort
1987	Reduction from quad to twin gear, mid-year closure, ban on daylight trawling during the tiger prawn season
1988	Restriction on headrope-length of nets
1990	Voluntary industry-funded buyback scheme with loans from the government (failed to reduce the fleet as much as intended although 172 trawlers left the fishery)
1993	Compulsory, industry-funded, buy-back scheme (reduced the fleet to 137 (128 active) vessels). Removal of net-size restrictions (but use of twin gear only remains)
1995	Start of annual assessments of tiger prawns
1997	The fishery is closed 3 weeks earlier at the end of the 2nd sub-season and during the mid-season closure for 1998
1998	Mandatory introduction of satellite-based Vessel Monitoring System across the fleet. The end-of-season closure reverts to the end of November and a large spatial closure is implemented on 1 November
1999	The spatial closure implemented in 1998 is replaced by larger mid-year and end-of-year closures
2000	Gear-based management starts in July and gear is reduced by 15%. Turtle Excluder Devices become compulsory in the tiger prawn fishery
2001	Gear units are reduced by a further 25%. Turtle Excluder Devices become compulsory in banana prawn fishery. The recovery target of S_{MSY} is set to be achieved by 2006
2002	The mid-season closure is extended
2005	The target for the fishery is changed to Maximum Economic Yield and gear is reduced by a further 25%

reduce the size of the fleet (Table 1) have led to a marked drop in the number of vessels in the fishery (from 280 vessels in the 1980s to the present fleet of 85; Dichmont et al., 2006a). However, this did not equate to an equivalent reduction in fishing mortality because, for example, of the fleets' increased ability to locate and catch prawns through changes in fishing power (or fishing efficiency) (Bishop et al., 2000; Dichmont et al., 2003a; Cartwright, 2005).

Between 1985 and 2001, each vessel was assigned a transferable Statutory Fishing Right (a form of individual property right) in the form of a number of “A-units”, a quantity based on vessel volume and engine horse power. This system was inflexible, however, because even small reductions in the number of A-units that was allowed in the fishery could result in boats being unable to fish, which impeded fleet restructures. A Statutory Fishing Right is now defined in terms of headrope length, with a specified total length for the fleet. A 25% reduction in gear units leads to a 25% reduction in headrope length per vessel. Vessels can either buy more units to restore their total headrope length (thereby leading to vessels leaving the fishery) or fish with a smaller net. As a result, a reduction in the number of gear units leads to an overall decline in fishing effort through the combination of a fleet restructure or vessels fishing with reduced fishing power.

The fishery generally starts at the beginning of April and there is a mid-season spawning closure from mid-May to end-July. The length of the mid-season closure has also been used to control effort in the past; the differential migration of the two tiger prawn species (Dichmont et al., 2001, and references therein; Dichmont et al., 2003b) leads to *P. esculentus* being more available to the fishery in winter than *P. semisulcatus*. As a result, a shorter season in the winter months would tend to shift effort from *P. esculentus* to *P. semisulcatus* and a change to the season at the end of the calendar year would have the opposite effect.

Management Strategy Evaluation (MSE) is a simulation framework that considers the whole management system (see Fig. 1 of Dichmont et al., 2006a, for an outline of the approach). It consists of an operating model that can be regarded as a representation of the “true” underlying dynamics of the resource and the fishery, and which can be used to generate the types of data typically collected from the fishery. In addition, there is a management strategy that analyses the fishery and/or monitoring data generated by the operating model (but remains “ignorant” of the underlying dynamics of the operating model) and a set of decision rules that determine the management actions to be taken given the results of assessment (e.g. the level of effort to be applied in the next year). The modelled management advice is fed back to the operating model where it can influence the dynamics of the “true” stocks being managed. An initial phase, referred to as conditioning, is required to determine the values for the parameters of the operating model so that these are consistent with the available historical information. The performance of a management strategy is summarized using performance measures that are derived from stated management objectives. The values for the performance measures are based on the “true” resource, as defined by the operating model. The performance of the assessment procedure component of a management strategy can be evaluated by comparing the estimates produced by it with the corresponding (and hence “true”) quantities in the operating model.

The MSE approach has been demonstrated to be an effective way to compare and evaluate alternative management strategies (combinations of data collection schemes, methods of data analysis and decision rules). Management strategies have been evaluated for many fisheries at the single- or the multi-species level) and, in recent years, for ecosystem objectives (Dichmont et al., 2006a, and references therein).

It is essential that the complete range of uncertainties (e.g. those related to biology, fleet dynamics, and how management decisions are implemented) are identified and modelled so that the effects of uncertainties on performance measures and estimation performance can be quantified. In the case of the NPF, an important feature of the management system is that the fishery is managed using input controls thereby requiring explicit modelling of the uncertainty involved in setting and implementing effort levels.

This paper uses the operating model of Dichmont et al. (2006a) to examine management strategies and assessment procedures considered for actual use in the NPF. Three alternative assessment models are used to determine the total amount of effort to be expended on tiger prawns in a year, and in some cases, also the season length. These three assessment models differ in terms of complexity, population dynamic assumptions, and spatial and temporal resolution. The analyses of this paper explore the performance of several management strategies for one operating model while Dichmont et al. (2006b) explore the impact of the specifications for the operating model for one decision rule using the three alternative assessment methods. The multi-species and input control nature of this fishery makes it relevant to similar trawl and non-trawl fisheries worldwide.

2. Methods

2.1. The operating model

Dichmont et al. (2006a) provide the detailed specifications of the operating model. In brief, the tiger prawn resource is represented using a 5-stock, two-species population dynamics model with the number of tiger prawn stocks and their boundaries determined using expert opinion (see Dichmont et al., 2001, for details). Banana prawns are represented in the operating model by assuming that historical catch levels reflect the best appraisal of future catches.

The operating model and the management strategies are linked though the data generation and the effort allocation modules; the data generation module provides the data (with uncertainty) used by the assessment procedure based on simulated monitoring of the "true" resources, while the effort allocation module determines the fishing mortality on the "true" resources given the output from the decision rule and the vagaries associated with implementing management decisions in the real world.

The data used for assessment purposes are logbook catch and effort data, either disaggregated to species and week, or aggregated to year and over both tiger prawn species. These data are assumed to be measured without error. No errors are assumed between the boundaries used for stock assessment and the true boundaries among the stocks, although this could be examined in future using the methods of Punt et al. (1995) and Punt (2003). Once the data have been generated, they are analyzed using the stock assessment component of the management strategy and then by its decision rule component. This leads to a total tiger prawn effort and (for some management strategies) specification of season length. The total tiger prawn effort and season length are passed back to the operating model and determines the tiger prawn effort by stock area, week and tiger prawn species (see Dichmont et al., 2006a, for details).

2.2. Management strategies

The management strategies are based on choices regarding the assessment procedure and the decision rules. A total of 17 management strategies are considered in the analyses of this paper. The following sections outline how these management strategies were designed.

2.2.1. Assessments methods

Three stock assessment methods are evaluated: a linear regression of the log-catch rate on time, a biomass dynamic model and a Deriso-Schnute delay-difference model. The model types, the data they use, and the species and spatial scale at which they can be applied are described in Table 2. The details of the biomass dynamic and Deriso-Schnute models as applied to the NPF are described in Haddon (2001) and Dichmont et al. (2003b), respectively. These assessment procedures capture a range from very simple (a linear regression of log-catch-rate on time) to fairly complicated (an age- and stock-based assessment model). The linear regression approach is not a stock assessment method *per se*, but is rather a simple analysis from which to produce management advice; its performance can be used as a base-line against which to evaluate the relative utility of applying management strategies based on the more complex stock assessment models.

Some of these assessment methods can be refined further in terms of the data used (e.g. raw catch rates, standardized catch rates, survey data) and the spatial scale at which they can be applied (e.g. NPF-wide or by "stock area"). The most obvious differences are that the cpue regression approach does not assess the status of the resource, uses annual data and is not species-specific, the biomass dynamic model assesses the status of the two tiger prawn species combined on an annual basis, and the Deriso-Schnute model assesses the status of each tiger prawn species separately using a weekly model that accounts for inter-annual changes in recruitment. Other fundamental differences among the assessment methods relate to: (a) whether account is taken of changes over time in fishing efficiency ("fishing power") and how the catchability coefficient is determined. Fishing power and catchability are not used in the cpue regression approach, are estimated internally in the biomass dynamic

Table 2
The specifications of the stock assessment methods

Model	Overview	Data used	Species	Number of stocks
Linear	The slope of a linear regression of log-catch-rate on year over the past 5 years	Unstandardized catch rate over 5 years	Species-aggregated	Single stock
Biomass dynamic	A biomass dynamic model that estimates six parameters	Total annual tiger prawn catches and annual catch rates standardized with respect to week and stock area	Species-aggregated	Single stock
Deriso-Schnute	A weekly model that estimates annual recruitment and a stock-recruitment relationship	1. Catch, effort, fishing power	Species-disaggregated	1. Single stock
		2. Catch, effort, fishing power and survey index		2. Multiple stocks

model, and are input parameters for the Deriso assessment. It should be noted that the Deriso-Schnute model (referred to hereafter as the "Deriso model") is presently the standard stock assessment model used in the management of the NPF tiger prawn fishery.

The output quantities obtained from the three assessment procedures differ:

(1) Linear regression (prefix "C" in the management strategies)—the slope and intercept of a straight line regression of the logarithms of the catch rates on year for the most-recent 5 years.
(2) Biomass dynamic model (prefix "B")—the intrinsic growth rate, carrying capacity, Pella-Tomlinson shape parameter, the catchability coefficient in 1993 and biomass time-trajectory.
(3) The Deriso model (prefix "D")—the time-series of recruitments, and the parameters of the stock-recruitment relationship (steepness, virgin stock size, stock-recruitment variance and temporal autocorrelation in recruitment) by species.

2.2.2. Decision rules to calculate tiger prawn target effort and season length

The tiger prawn effort (aggregated over stock area) and the season length are determined according to one of two options depending on whether an assessment is conducted or not. Note that to mimic past practice, scientific recommendations to change effort levels are only implemented with a probability of 1/3 (Dichmont et al., 2006a).

2.2.2.1. An assessment is not conducted. If no stock assessment is conducted, the intended effort targeted at tiger prawns during year y, $E^{\text{int}}_{\text{target},y}$, is determined using the equation:

$$E^{\text{int}}_{\text{target},y} = \sum_{a} E_{a,y-1}\left(1.0 + \frac{1}{2}\text{Slope}\right)$$

where $E_{a,y-1}$ is the effort targeted at tiger prawns during year $y-1$ for stock area a and Slope is the slope of the linear regression of log-catch rate on year.

The season length for this management strategy is fixed equal to that for 1995 and the regression for year y is conducted using data for years $y-5$ to $y-1$. Whether the effort intended increases or decreases from the previous year depends on the sign of the slope and the extent to which it increases/decreases depends on the magnitude of the slope.

2.2.2.2. An assessment is conducted. If a stock assessment is conducted using either the biomass dynamic or Deriso models, the effort decisions are based on attempting to move the spawning stock size to some fraction of that at which MSY is achieved (S_{MSY}). Three input settings determine how precautionary the effort level will be: (a) the maximum proportion of E_{MSY} (the effort at which MSY is achieved on average) at which tiger prawn effort can be set, (b) the proportion of S_{MSY} at which this maximum proportion of E_{MSY} is set and (c) the spawning stock size below which effort is zero (Fig. 1). This decision rule can be

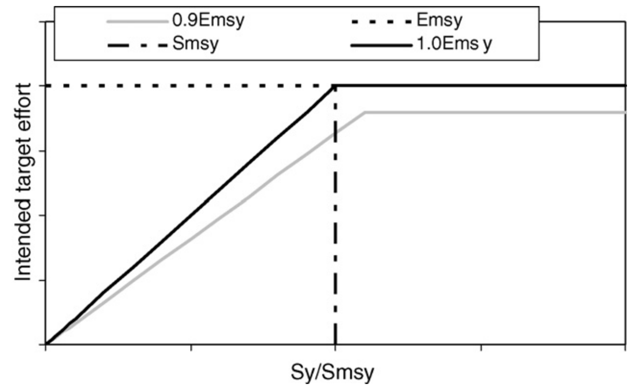

Fig. 1. The tiger prawn effort decision rule. Two example decision rules are given; one with S_{MSY} as the target and another that is more precautionary.

tuned to leave the spawning stock size at, below or above S_{MSY}. The effort directed towards tiger prawns is the sum of the efforts estimated to be targeted at each tiger prawn species separately.

Determining the season length from the results of the assessment is not straightforward because there is little historical precedent. However, the decision rules described in Fig. 2, which use the estimate of the ratio of the spawning stock size for the most recent year to S_{MSY} describes past decisions adequately; the mid-year season closure is generally extended when the brown tiger prawn assessment is pessimistic whereas the end of year season date and the second season start date are generally adjusted based on the results of the assessment of grooved tiger prawns. The start of the season was fixed to be 1 April because this has been the start date of the fishery for many years (except for 2004 when a mid-April start date was implemented). The ideal season opening and closed dates are calculated separately for each species using Fig. 2. Since only a single set of season dates are ultimately implemented, the intersection of the weeks of overlap is selected as the season to be implemented—this can be interpreted as conservative, but realistic. This means that only weeks which were set as open for both species independently of each other would be fished.

Three additional ways of changing the season in response to changes to the estimates of S_y/S_{MSY} by species (Fig. 2) are explored in the light of the generally poor performance at leaving the spawning stock size of *P. esculentus* at or above S_{MSY}. The "short 1st season" option (Fig. 2, centre panels) is the same as the "Base Case" option (Fig. 2, upper panels), except that it opens the season in week 14 and closes it in week 22 (closing the fishery after week 21 is a means of eliminating the catch of tiger prawns, which consist mostly of *P. esculentus*, during the first season) while the "short 1st and 2nd season" option (Fig. 2, lower panels) is the same as the "short 1st option", except that the opening date for the second season is moved from week 31 to week 33 to reduce the effort directed towards *P. esculentus*.

2.3. Performance measures

The analyses involved 120 simulations in which the operating model was projected from 2003 to 2015. This number of simulations provides greater than 95% certainty that 95% of

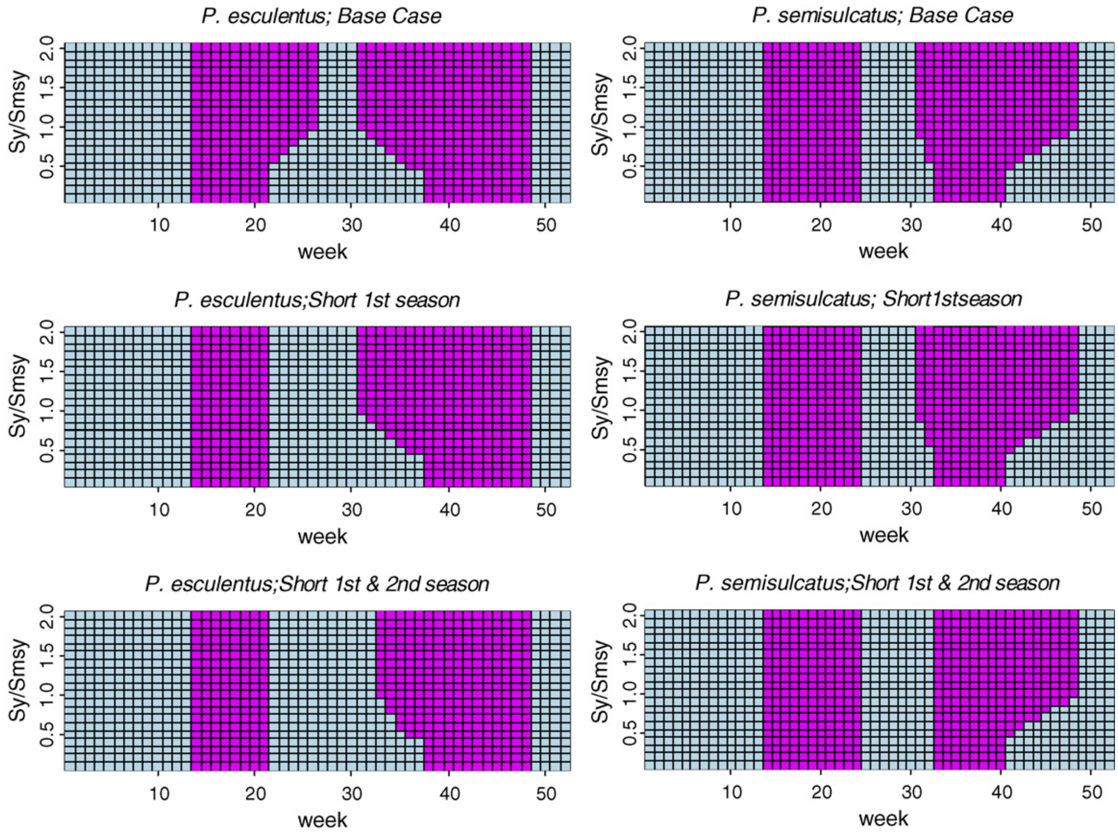

Fig. 2. Options used when determining the specifications for the season (dark grey is open to fishing and light grey is closed) as a function of the ratio of the current spawning stock size to S_{MSY} for each species. Three options are shown; the Base Case, "short 1st season" and "short 1st and 2nd season".

the distribution is covered. Only three performance measures are considered in this paper (see Dichmont et al., 2006b, for a complete list of the performance measures considered in the full MSE) because these are sufficient to illustrate the key aspects of the performances of the various management strategies. The risk-related performance measure is the ratio of the spawning stock size in 2010 to S_{MSY} (abbreviation S_{2010}/S_{MSY}) and the two economic-related performance measures are: (a) catch variability (AAV—the median over simulations of the average annual absolute variation in catches expressed as a percentage of the total catch) and (b) long-term catch (DCatch—the median over simulations of the annual discounted catch; the discount rate is assumed to be 5% per annum—T. Kompas, Australian National University, personal communication). The estimation-related performance measures are the magnitude of the relative error (expressed as a percentage) between the estimated and the true values for annual recruitment, S_y/S_{MSY}, the steepness of the stock-recruitment relationship, E_{MSY}, and S_{MSY}.

3. Results

The results are based on a single operating model with the objective to identify which management strategies are able to leave the spawning stock size for both tiger prawn species close to the target reference point, S_{MSY}. In addition, an ideal management strategy should avoid possible adverse consequences:

(1) it should not have a low long-term discounted catch;
(2) it should not have high inter-annual variation in catches.

An assessment of resource status is undertaken each year, which then determines the total effort level and the season length for the management strategies based on the biomass dynamic and the Deriso models. In contrast, no assessment of resource status is made for the cpue regression approach, but the decision rule is applied every year.

3.1. Alternative "assessment" methods

3.1.1. Management-related performance

The "Base Case" management strategies based on the three assessment procedures in which the data are aggregated over stock (abbreviations "B-1 stock BC", "C-1 stock BC" and "D-1 stock BC") are compared in Table 3. This table lists the medians and 90% intervals for S_{2010}/S_{MSY} for *P. semisulcatus* and *P. esculentus*, and the median and 90% intervals for the two economic-related performance measures. The target effort for both species is E_{MSY}. None of the management strategies leaves the spawning stock sizes for both species above S_{MSY} simultaneously. The cpue regression approach ("C-1 stock BC") leaves the spawning stock size of *P. semisulcatus* above S_{MSY} in median terms and that of *P. esculentus* slightly below S_{MSY} in median terms. The higher spawning stock sizes achieved by the cpue

Table 3
Specifications for the 17 management strategies and the resultant values for the performance measures (medians and 90% intervals)

Abbreviation	First season dates (weeks)	Second season dates (weeks)	Target effort (fraction of E_{MSY})	Target Reference Point (fraction of (S_{MSY})	No. of assumed stocks	S_{2010}/S_{MSY} (%)		Discounted catch: DCatch (‘000 tonnes)	AAV
						P. semisulcatus	*P. esculentus*		
B-1 stock BC	14–26	31–48	1	1	1	103 (81–128)	82 (57–106)	24.9 (22.4–27.5)	17.3 (11.2–43.7)
C-1 stock BC	14–26	31–48	1	1	1	115 (94–148)	95 (69–120)	24.1 (21.9–26.7)	10.4 (6.3–15.3)
C-3 stock	14–26	31–48	1	1	3	116 (94–148)	95 (70–120)	24.1 (21.8–26.7)	10.3 (6.3–15.3)
C-4 stock	14–26	31–48	1	1	4	116 (94–148)	95 (70–120)	24.1 (21.8–26.7)	10.2 (6.2–15.3)
D-1 stock BC	14–26	31–48	1	1	1	100 (79–128)	80 (58–104)	25.5 (22.8–28.7)	12.9 (9.2–18.3)
D-3 stock	14–26	31–48	1	1	3	97 (84–130)	79 (56–100)	26.0 (24.1–27.9)	12.1 (8.6–16.1)
D-4 stock	14–26	31–48	1	1	4	95 (83–129)	78 (55–99)	26.1 (24.0–27.8)	12.1 (8.3–16.1)
D-0.8Emsy	14–26	31–48	0.8	1.2	1	115 (92–146)	93 (70–119)	24.3 (21.7–27.4)	11.3 (6.8–16.5)
D-0.6Emsy	14–26	31–48	0.6	1.5	1	130 (104–163)	107 (82–136)	21.7 (19.2–24.4)	13.3 (8.4–18.6)
D-0.4Emsy	14–26	31–48	0.4	1.6	1	145 (117–178)	121 (94–154)	18.1 (15.8–20.2)	17.4 (12.8–22.4)
D-mixed TE 1	14–26	31–48	1.0 for PS; 0.7 for PE	1.0 for PS; 1.3 for PE	1	106 (85–137)	87 (64–111)	25.1 (22.4–28.1)	11.9 (7.7–17.7)
D-mixed TE 2	14–26	31–48	1.2 for PS; 0.4 for PE	0.8 for PS; 1.6 for PE	1	101 (82–129)	82 (57–105)	25.5 (22.8–28.5)	12.1 (7.4–17.3)
D-mixed TE 3	14–26	31–48	1.0 for PS; 0.2 for PE	1.0 for PS; 1.8 for PE	1	117 (101–149)	99 (70–123)	24.0 (22.4–25.4)	10.3 (6.7–16.8)
D-mixed TE 4	14–26	31–48	1.0 for PS; 0.6 for PE	1.0 for PS; 1.4 for PE	1	108 (92–139)	89 (64–111)	25.4 (23.3–26.7)	11.7 (7.9–17.5)
D-short 1st season	14–21	31–48	1	1	1	97 (76–125)	86 (62–109)	25.6 (22.8–28.8)	12.7 (8.6–18.1)
D-short 1st and 2nd season	14–21	33–48	1	1	1	97 (76–124)	86 (62–110)	25.6 (22.8–28.7)	12.8 (8.6–18.4)
D-mixed TE 2 short 1st season	14–21	31–48	1.0 for PS; 0.6 for PE	1.0 for PS; 1.4 for PE	1	105 (90–138)	95 (67–117)	25.4 (23.4–26.8)	11.3 (7.7–17.0)

PS is *P. semisulcatus*, PE is *P. esculentus*, and TE is Target Effort.

regression approach compared to the Deriso-based management strategy come at a cost of slightly (about 5% in median terms) lower total discounted catches. Interestingly, "C-1 stock BC" performs better than "D-1 stock BC" in terms of minimizing inter-annual catch variability (median AAVs of 10.4% compared to 12.9%). Management strategies "B-1 stock BC" and "D-1 stock BC" both leave the spawning stock size for *P. semisulcatus* close to the target level on average, but are unable to do so for *P. esculentus*, the spawning stock size of which is generally well below S_{MSY} in 2010. The management strategy based on the biomass dynamic model ("B-1 stock BC") leads to the largest inter-simulation variance in the values for the economic-related performances measures although the median values for $S_{2010}/S_{\mathrm{MSY}}$ are similar to those for management strategy "D-1 stock BC" (Table 3).

The results in Table 3 are mimicked when expressed by stock area (Fig. 3); some stocks are left close to S_{MSY} while others are left above or below this level. The poorest performance occurs for *P. esculentus* in the Karumba stock area.

3.1.2. Performance of the assessment

Relative error distributions for spawning stock size and recruitment for the Deriso model assessment procedure when it is applied in 2010 and relative error distributions for S_{MSY},

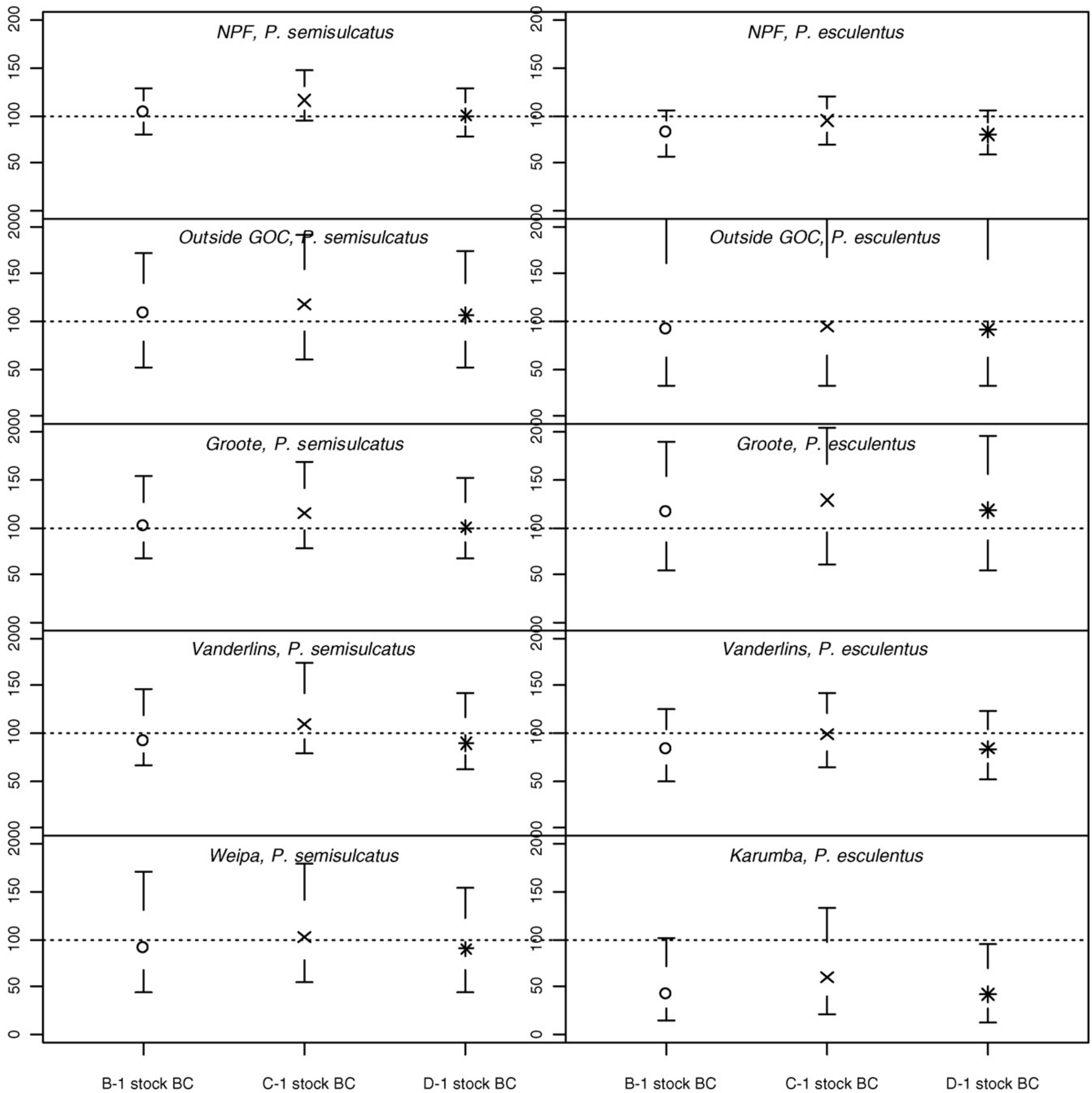

Fig. 3. Medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY}, for each of the stock areas and species in the operating model. Results are shown for the "B-1 stock BC" (biomass dynamic model), the "C-1 stock BC" (cpue regression approach) and the "D-1 stock BC" (Deriso model) management strategies.

E_{MSY} and stock-recruitment steepness for this model when it is applied in 2003, 2006 and 2010 are given in Fig. 4. The estimates of recruitment for *P. semisulcatus* are, apart from those for the early years and for 2002, generally unbiased. The estimates of stock-recruitment steepness for *P. semisulcatus* are, however, negatively biased which leads to bias in the estimates of management-related quantities such as S_{MSY} (positively) and E_{MSY} (negatively). Any bias in the ratio S_y/S_{MSY} is therefore due primarily to bias associated with S_{MSY}. There are no obvious signs that the estimates of recruitment for *P. esculentus* are positively or negatively biased. Furthermore, the estimates of S_{MSY} are also close to unbiased, even though the estimates for E_{MSY} and steepness are negatively biased (Fig. 4). It is surprising then that the "D-1 stock BC" management strategy is able to leave the spawning stock size of *P. semisulcatus* close to S_{MSY}, whereas this strategy leaves the spawning stock size of *P. esculentus* well below S_{MSY}. It is perhaps noteworthy that there is no evidence for learning, because the estimates of S_{MSY}, E_{MSY} and stock-recruitment steepness are as biased in 2010 as they were in 2003.

The estimates of the parameters of the biomass dynamic model imply a resource that is huge and very unproductive (results not shown). Furthermore, the parameter estimates vary substantially among simulations. This variation is reflected by the larger inter-simulation variation in the values for the economic-based performance measures for the "B-1 stock BC" management strategy in Table 3.

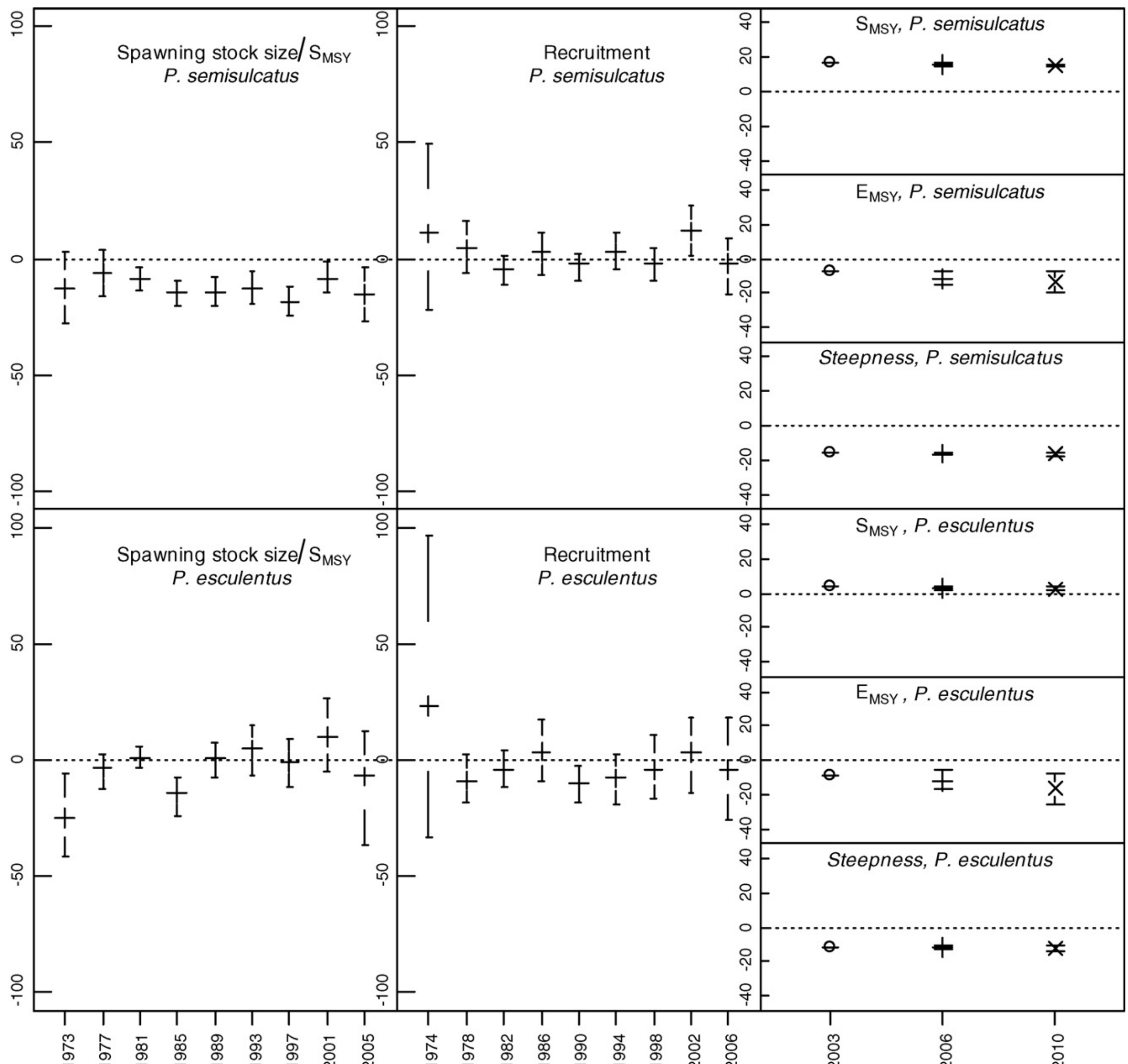

Fig. 4. Medians and 90% intervals of the percentage relative error distributions for the "Base Case" Deriso assessment model (management strategy "D-1 stock BC"). Results are shown for spawning stock size and recruitment by year when the assessment is conducted in 2010, and S_{MSY}, E_{MSY} and the steepness of the stock-recruitment relationship for assessments conducted in 2003, 2006 and 2010.

3.2. Multi-stock assessment methods

3.2.1. Management-related performance

Performance measures for management strategies based on assessments that are applied at finer spatial resolution than the "Base Case" management strategies are shown in Table 3. It might be expected that these management strategies would perform better than the "Base Case" management strategies because they would better capture the true underlying stock structure. The variant of the "Deriso" management strategy based on a 3-stock assessment (abbreviation "D-3 stock") includes an outside Gulf stock ("Outside GOC"; see Dichmont et al., 2006a, for a map), a western Gulf stock (the Groote and Vanderlins stock areas combined) and an eastern Gulf stock (the Karumba and Weipa stock areas combined) whereas that based on a 4-stock assessment (abbreviation "D-4 stock") is based on assuming that each of the Outside GOC, Groote and Vanderlins stock areas contain a single stock, and that the eastern Gulf (the Karumba and Weipa stock areas combined) is a single stock. The 4-stock assessment is equivalent to the true stock structure in the operating model because *P. semisulcatus* is assumed not to be found in the Karumba stock area and *P. esculentus* is assumed not be found in the Weipa stock area in the operating model (Dichmont et al., 2006a).

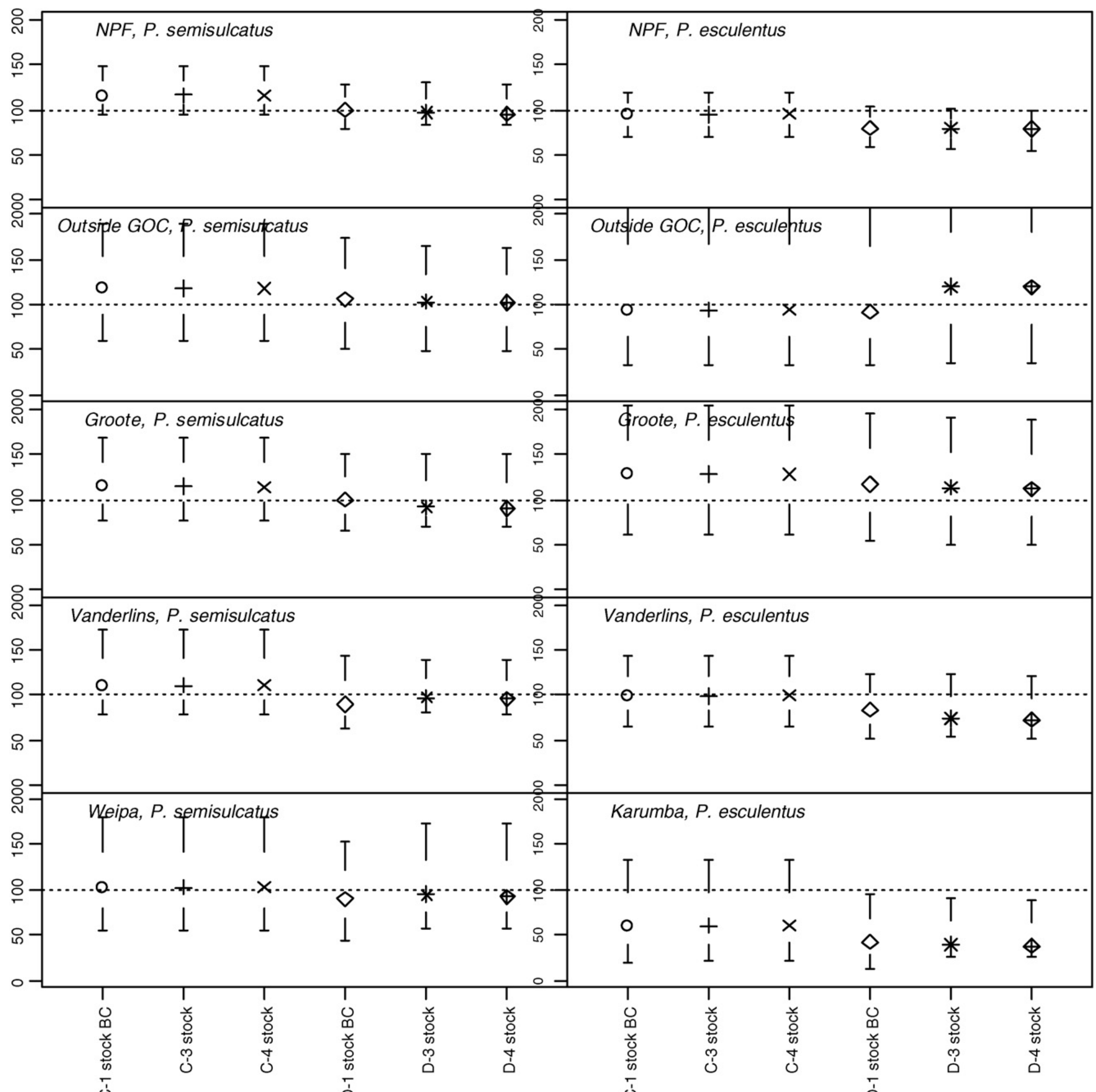

Fig. 5. Medians and 90% intervals for the spawning stock size in 2010 relative to S_{MSY}, for each of the stock areas and species in the operating model. Results are shown for the Deriso model-based (prefix "D") management strategies and the cpue regression (prefix "C") based on a single stock ("1 stock BC"), 3 stocks ("3 stock") and 4 stocks ("4 stock").

Unfortunately, there is little evidence for improved performance in terms of leaving the spawning stock size close to S_{MSY} when assessments better reflect the true underlying stock structure (Fig. 5) although the inter-simulation variability and inter-annual variation in catches is less for the management strategies based on the 3- and 4-stock assessments.

3.2.2. Estimation performance

There are some noteworthy differences in estimation performance between the 4-stock Deriso assessments (Fig. 6; the results for the 3-stock assessments are similar to those for the 4-stock assessments, and are consequently not shown) and those for the corresponding single-stock assessments (Fig. 4). Specifically, the bias of $S_{\mathrm{y}}/S_{\mathrm{MSY}}$ for *P. semisulcatus* becomes increasingly negative over time in the eastern Gulf (Weipa in Fig. 6); this trend pertains to *P. semisulcatus* in the Weipa stock area because *P. semisulcatus* is not found in the Karumba stock area. The widths of the intervals in Fig. 6 tend to be wider than those in Fig. 4, although this is perhaps not surprising given that the multi-stock assessments estimate more parameters from the same amount of data. This is perhaps most evident for the estimates of $S_{\mathrm{y}}/S_{\mathrm{MSY}}$ for *P. esculentus*. Unlike the case when considering a single stock (Fig. 4), the estimates of E_{MSY}, steepness and S_{MSY} are biased for some of the putative stocks (e.g. *P. semisulcatus* in the "Weipa" stock area, *P. esculentus* in the "Groote" stock area). What is perhaps somewhat disturbing is that the relative error distributions for S_{MSY} and E_{MSY} actually get larger in some stocks as time progresses; the reasons for this remain unclear.

3.3. Changing the total effort

The probability of leaving the stocks at (or above) S_{MSY} is less than desired when the decision rule is based on setting effort to E_{MSY} when the stock is perceived to be above S_{MSY}. The sensitivity of the performance measures for the Deriso model-based management strategies to changing maximum proportion of E_{MSY} at which tiger prawn effort can be set is therefore explored in Table 3. As expected, both risk (e.g. $S_{2010}/S_{\mathrm{MSY}}$) and economic performance measures are reduced as this proportion (target effort or TE) is decreased from 1.0 to 0.4. The spawning stock size of *both* species exceeds S_{MSY} in 2010 with greater than 50% probability only when TE is 0.6 or less. There is a greater than 70% probability that the spawning stock size will exceed S_{MSY} in 2010 when TE is between 1.0 and 0.8 for *P. semisulcatus* and 0.6 and 0.4 for *P. esculentus*. This conclusion remains generally valid even when the results are analyzed by stock area, except that *P. esculentus* in the Karumba stock area does not quite recover to S_{MSY} even when TE is set to 0.4.

The values for the economic- and risk-related performance measures change in different ways as TE is decreased from 1.0 to 0.8. Specifically, the proportional increase in spawning stock size is much greater than the proportional reduction in catch (Fig. 7). However, large reductions in the economic-related per-

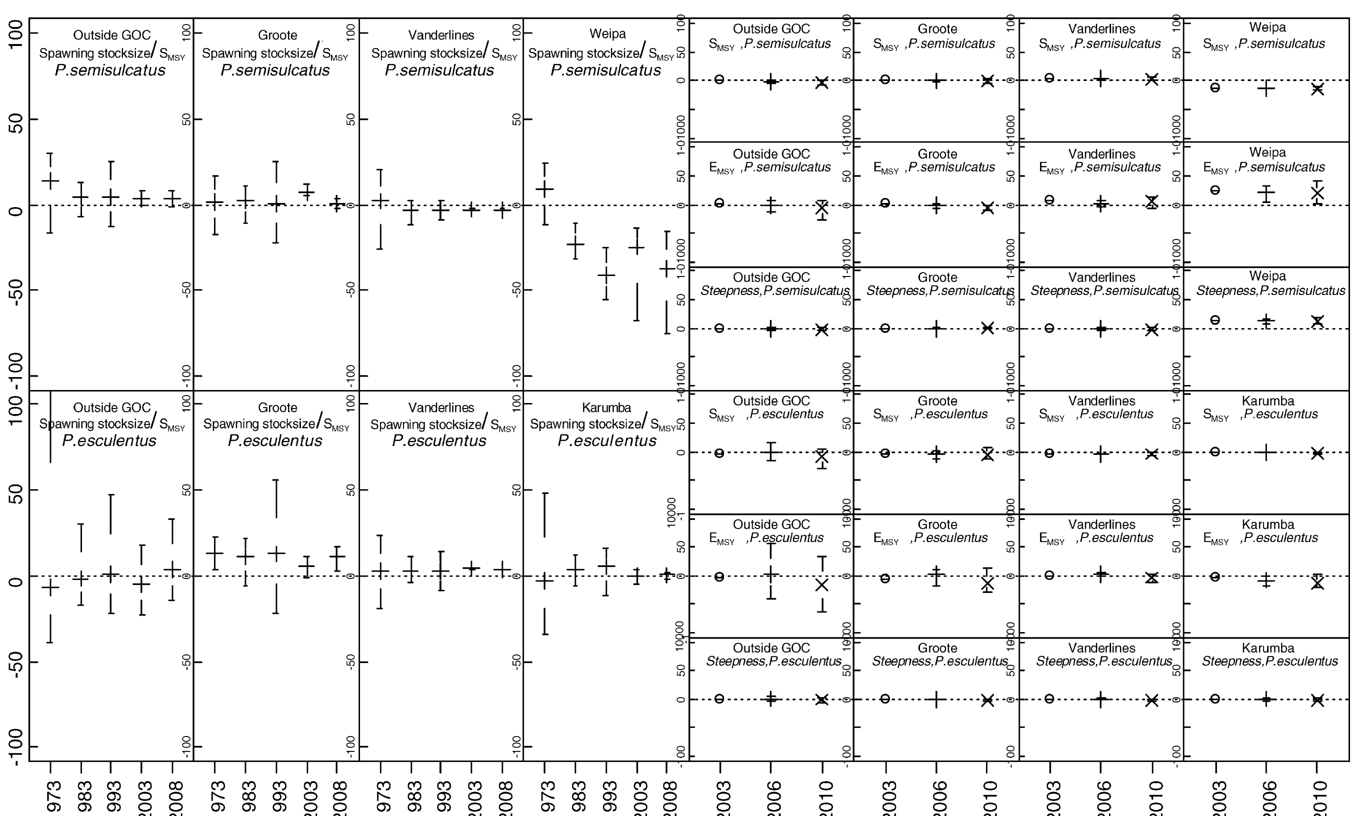

Fig. 6. Medians and 90% intervals of the percentage relative error distributions for the 4-stock Deriso assessment model. Results are shown for spawning stock size and recruitment by year when the assessment is conducted in 2010, and S_{MSY}, E_{MSY} and the steepness of the stock-recruitment relationship for assessments conducted in 2003, 2006 and 2010.

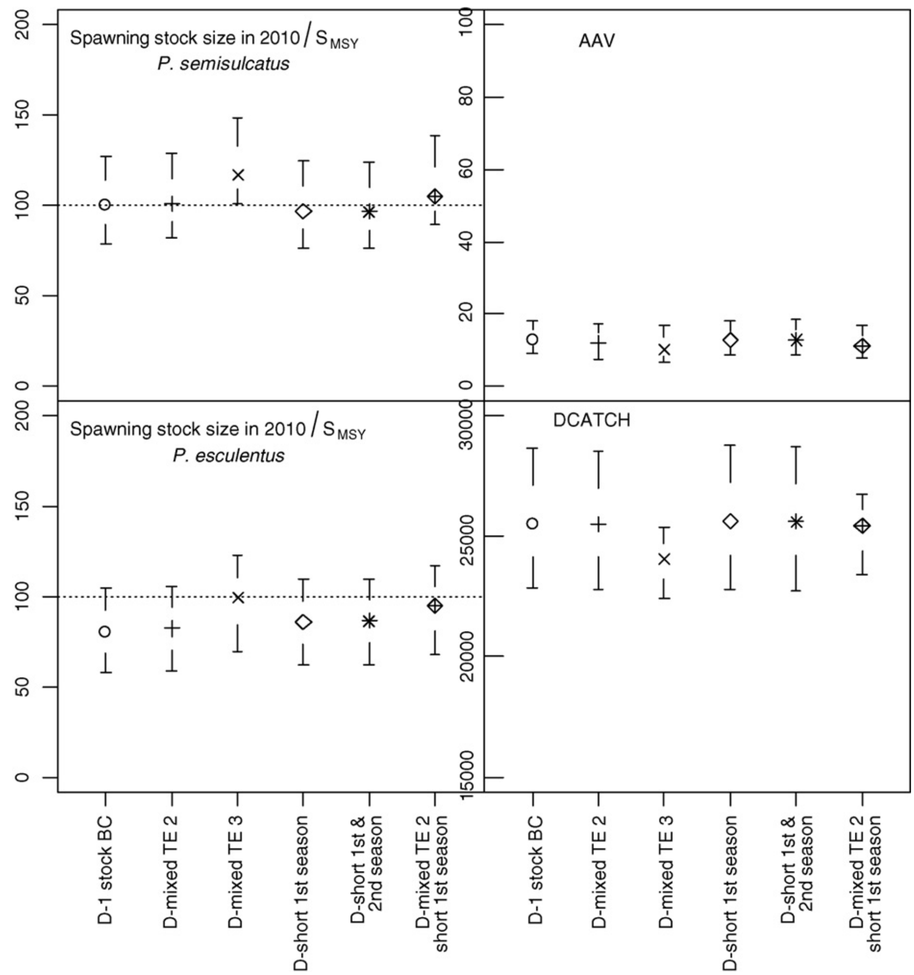

Fig. 7. Management and economic-related performance (medians and 90% intervals) for Deriso (D) model-based management strategies which differ in terms of the target effort level and/or the season dates (see Table 3 for the specifications of the management strategies).

formance measures occur once TE decreases below 0.8. There is thus a large reduction in risk by decreasing TE from 1.0 to 0.8, with only a relatively small loss in reward.

Performance measures for several species-specific choices for TE are also given in Table 3: "D-mixed TE 1" (1.0 for PS and 0.7 for PE), "D-mixed TE 2" (1.2 for PS and 0.4 for PE), "D-mixed TE 3" (1.0 for PS and 0.2 for PE) and "D-mixed TE 4" (1.0 for PS and 0.6 for PE). The specifications for these management strategies are based on the results above, which suggest that the probability of leaving the spawning stock size of *P. esculentus* at or above S_{MSY} is improved by decreasing TE. The probability of being above S_{MSY} is higher for both species for management strategy "D-mixed TE 2", but this management strategy still results in a median spawning stock size less than S_{MSY} for *P. esculentus*. This is possibly because the total effort from the management strategy applies to both tiger prawn species combined, so that S_{2010} for *P. semisulcatus* is increased even though the aim was to reduce fishing pressure on *P. esculentus*.

The inability to leave both species near S_{MSY} by manipulating the species-specific TE values is further evidence that the overlapping geographical distributions of the two tiger prawn species, combined with their differing biology and the lack of spatial management, makes attempting to manage them separately very difficult.

3.4. Changing how the season length is set

Changing how the season length is modified given the results of the assessment does not impact estimation performance (results not shown). A more restrictive first season ("D-short 1st season") seems to move the effort directed towards *P. esculentus* by management strategy "D-1 stock BC" to being directed at *P. semisulcatus* as the effort gets concentrated into the second season (Table 3; Fig. 7). One consequence of this is that, although there is some increase in the probability of the spawning stock size of *P. esculentus* being above S_{MSY}, there is now less than a 0.5 probability of the spawning stock size of *P. semisulcatus* being above S_{MSY} (Table 3). Shortening the first season and starting the second season later ("D-short 1st and 2nd season") causes only a slight shift in effort from *P. esculentus* to *P. semisulcatus* (Fig. 7). Overall, therefore, changing how season length is modified in response to changes in abundance (without changing the total effort) is not sufficient to allow the management strategies to leave the spawning stock size of both species at or above S_{MSY}.

3.5. Combining different input mechanisms

The impact of simultaneously varying the maximum proportion of E_{MSY} at which tiger prawn effort is set (TE) and the weeks that define the season is highlighted in Fig. 7. Of the various management strategies in Fig. 7, "D-mixed TE 2 short 1st season" comes closest to leaving both species at S_{MSY} in median terms. Interestingly, this management strategy also performs well in that it does not reduce discounted catch or increase inter-annual variability in catches compared to "D-1 stock BC". This management strategy also exhibits less inter-simulation variance in discounted catch than "D-1 stock BC".

4. Discussion

The objective of this paper is not to determine which target reference point is most appropriate for the NPF (this is largely a socio-political decision), but rather, given a target reference point (in this case S_{MSY}), how well are we able to achieve it with input controls, preferably without compromising catch stability or catch itself. The focus on S_{MSY} is because S_{MSY} was selected in 2001 to be the target for the fishery and that recovery to S_{MSY} should occur by 2006 (see Table 1), after which S_{MSY} would be a limit reference point, and the spawning stock size at which Maximum Economic Yield is achieved would be the target reference point (Annie Jarrett, Northern Prawn Management Advisory Committee secretary, personal communication).

4.1. Choosing the appropriate assessment method

None of the management strategies managed to leave the spawning stock size of both tiger prawn species at S_{MSY} in median terms simultaneously, even though species-specific assessments are conducted for the management strategies based on the "Deriso" model. Furthermore, the comparison of the results for the cpue regression approach (which does not involve fitting dynamic models to data) and those for the management strategies based on the "Deriso" model demonstrates that the additional complexity of a stock assessment based on a population dynamic model does not necessarily reduce risk. Several factors, either alone or in combination, probably contribute to the inability of the management strategies based on the sophisticated assessment model to out-perform the simpler management strategy:

(1) the assessment is biased to some extent;
(2) a global effort and season length are set by the management strategy whereas the seasonal and *spatial* pattern of fishing determines the amount of effort expended on each species (i.e. vessels are able to expend the available effort in any stock area; there is no spatial management); and/or
(3) the capture of pre-spawning individuals is difficult to avoid using only controls on total effort.

It seems likely that management will continue to expect estimates of management-related quantities such as spawning stock size relative to S_{MSY}. The problem associated with basing management decisions on the cpue-based decision rule is that there is no information on stock status for the managers unless an assessment is also undertaken. This means that the resources needed to provide scientific management recommendations are unlikely to be reduced if management was based on the cpue-based decision rule. Therefore, future management recommendations would have to be based, to some extent, on a management strategy that involves a stock assessment of some sort. In terms of the assessment models to be applied, of the two stock assessment methods considered in this study, there seems little reason not to continue with the use of the Deriso model-based assessment technique as it is the *status quo* and because without additional constraints, the alternative stock assessment method (the biomass dynamic model) appears to be unstable.

4.2. Countering fishery mobility

Management of fleets and fisheries that harvest multiple stocks is complicated. The less productive stocks in a mix of stocks may suffer unsustainable mortality while the more-productive stocks continue to support sustainable catches. Stocks harvested together may be at a very different status relative to safe biological limits, which leads to the need for several different harvest strategies in the same fisheries (Kell et al., 2004). This multi-species nature of the fishery is common in, amongst others, prawn fisheries, e.g. Queensland trawl (Williams, 2002), Gulf of Mexico shrimp (Garcia, 1997; Nance et al., 1994).

At present, the NPF controls effort through season length and the number of gear units. The "Base Case" management strategies of this paper therefore operationalize, through decision rules, the spirit of what management is trying to achieve and how it is trying to do it, i.e. effort is not allocated separately to each tiger prawn species, but the aim is nevertheless that the stocks of each species are left at or above S_{MSY}. Unfortunately, the extent to which each species is impacted by the effort level set depends mainly on the time of year and area being fished. Allocating effort NPF-wide means the fleet is able to choose which areas to fish. The implication of this is that it is not possible to leave the spawning stock size of *P. semisulcatus* near S_{MSY} while at the same time leaving the spawning stock size of *P. esculentus* near S_{MSY}. This result reflects the long-held expectation that it is not possible to achieve a catch of MSY for multiple species in a mixed-species fishery simultaneously.

Basing a management strategy on an assessment method that attempts to estimate stock status by species and area does not increase the probability of leaving the spawning stock size close to S_{MSY}. Rather, the inability to achieve the management goal is probably due to effort not being allocated directly to a specific stock area and species (which negates some of the possible benefits of a multi-stock/multi-area assessment). The Groote, Vanderlins and Karumba stock areas are likely to receive most of the effort irrespective of the total level of effort because the total biomass of all prawn species is high in these stock areas. Clearly, to be most efficient, input controls should allocate effort to each stock area directly. However, this solution is not likely to be perfect either because the two species mix spatially and temporally.

While it should be fairly straightforward to determine the amount of effort by area with high accuracy because all of the vessels in the fishery are monitored using a Vessel Monitoring System, only though a (costly) observer program would be possible to monitor the spatial resolution of the catches with sufficient accurately for legal enforcement purposes. This is because a vessel may fish in several areas during a trip.

4.3. Setting appropriate effort levels

Reference points can be Limits or Targets, depending on their intended usage (see Caddy and Mahon, 1995; Sissenwine and Shepherd, 1987). The difference between a target reference point (TRP) and a limit reference point (LRP) is important. The TRP is assumed to be the ideal state for the fishery (where the balance between long-term productivity and sustainability is optimised; Caddy and Mahon, 1995). On the other hand, the LRP is an agreed upon threshold state beyond which a fishery requires immediate and strong management measures to move it back towards the TRP. In the case of the NPF, the fishery moved in 2005 to using the Maximum Economic Yield as its TRP. However, this TRP is not considered in this paper because it is as yet undefined at the species level.

Since tiger prawn effort is not species-specific, mechanisms to maintain biological conservation objectives need necessarily be indirect. Three options are available: setting target effort by species, changing the season dates to shift effort from one species to the other (without changing the total effort) or a combination of the two.

4.3.1. Different target effort levels

Decreasing the maximum proportion of E_{MSY} at which tiger prawn effort can be set (TE) leads to higher spawning stock sizes (less risk) and lower catches (less reward). However, there is some non-linearity in the relationship between risk and reward as TE is decreased from 1 to 0.8. Given this non-linearity, the benefits of decreasing TE to slightly below 1 seem to outweigh the costs. However, costs, in terms of reduced catch, increase as TE is decreased below this threshold and, for example, if the TE is 0.4 the lowest catch during the projection period is close to 1000 tonnes per annum and the median discounted catch is only about 70% of that for a TE of 1. Catch rates would be higher if the stock size is higher (i.e. the profit for each vessel per unit effort may increase) and this will tend to offset the economic cost of the lower catches to some extent. However, the optimum value of TE cannot be quantified in the absence of detailed information about costs.

Interestingly, using different TEs for each species, which could be seen as a compromise between being risk averse and risky, often results in a median spawning stock size less than S_{MSY} for *P. esculentus*. This is because the total effort from the management strategy applies to both species, so that S_{2010} for *P. semisulcatus* is increased when TE is reduced despite the effort reduction directed towards *P. esculentus*. Obviously, setting and maintaining effort by species would best achieve the target reference point, but this is impossible to implement using input controls particularly because the two species mix spatially. In principle, output controls could be used to implement catch limits by species, but, as noted above, this would require major changes to the monitoring and compliance system in the fishery.

4.3.2. Changing the season

Since the season dates are changed in the simulations any time there is a need to do so (whereas there is only a 1/3 chance of changing total effort levels if this is deemed to be required), the specifications for season length may be an important factor in determining whether the spawning stock size is left at or above S_{MSY}. Furthermore, which weeks are open and which are closed to fishing indirectly determines how much effort is expended on each species. For example, much of the effort directed at tiger prawns during the first season and during the early part of the second season is automatically focused on *P. esculentus* because *P. semisulcatus* is generally unavailable at those times due to its migration pattern. It should be borne in mind that in these simulations a change in season does not reduce the total effort.

Another reason for the inability to leave the spawning stock at S_{MSY} on average is that the season length set when the spawning stock is assessed to be above the target level is such that capture of pre-spawning prawns is likely. Changing the algorithm that specifies season length was examined. However, unless the method used to specify the total effort is also changed, modifying this algorithm to avoid catching *P. esculentus* leads to a reduction in the spawning stock size of *P. semisulcatus*.

4.3.3. Mixed total effort and season inputs

A combination of shortening the first season and using a mixture of TEs by species produced the best results in terms of both risk and economic performance measures. This management strategy is also relatively easy to implement, results in no loss of economic performance and does not require effort to be allocated by area or species. However, the ability to utilize years of very good tiger prawn recruitment is effectively eliminated because the tiger prawn catch during the first season is greatly reduced.

The management of fisheries through input controls is particularly common in short-lived species, for example, the Falkland Island squid (Agnew et al., 1998; Barton, 2002), and several prawn resources (Exmouth Gulf, Australia (Penn et al., 1997), Queensland trawl, Australia (Williams, 2002), Torres Strait trawl (Turnbull and Watson, 1995), Gulf of Mexico shrimp (Garcia, 1997)). The results presented in this paper are very relevant to these fisheries as they manage effort between species using input controls.

5. Concluding remarks

The results of this paper highlight the difficulty of identifying simple management strategies for multi-species fisheries. None of the management strategies tested were able to leave the spawning stock size of *P. esculentus* (particularly that in Karumba stock area) near S_{MSY} if the target spawning stock size used in the management strategy was set to S_{MSY} even though the assessment model was based on the most of the same assumptions as the operating model. Trying to account for stock structure by conducting a spatially-structured assessment did not resolve this problem, most likely because, even if assessments are conducted spatially, there remain no restrictions on where in the NPF fishing is to occur. Since some stock areas have much higher abundances, and are consequently almost always heavily fished; effort remains in those stock areas irrespective of the status of the species present and much higher effort moves to those stock areas than is required to leave the spawning stock size of *P. esculentus* at (or above) S_{MSY}. Even reducing the total effort (by decreasing the target effort level in the decision rule) does not achieve the desired goal of reducing effort in stock areas such as Karumba and Mornington. It seems clear that some form of spatial management and allocation of effort may be required to ensure that all stocks of both species are at or above S_{MSY}. This may necessitate spatially-structured stock assessments. However, although spatially-structured assessments may reduce the bias caused by applying an assessment method to data for several stocks simultaneously, it should be noted that a spatially-structured assessment will be less precise because it needs to estimate more parameters from the same amount of data. In addition, stock boundaries, if they exist, are poorly known, with those available based only on expert opinion. Other concerns associated with moving to a spatially-structured stock assessment relate to the true number of stocks and the implications of movement among such stocks.

In the meantime, a combination of a short first season (or a mechanism that allows for banana prawn fishing but prevents tiger prawn fishing, such as a night-time closure) and a mixture of target effort levels that are much more precautionary for *P. esculentus* than for *P. semisulcatus* is needed to have a high likelihood of leaving the spawning stock sizes of both species near S_{MSY}.

In conclusion therefore, it is clear that the essential difficulty with regard to satisfying the current target reference point for each species is that the measure of control is total effort and that the species co-occur. The complex spatial and temporal changes in the relative distribution of the tiger prawn species means that even fairly complicated management strategies do not satisfy the management goals without being highly precautionary.

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