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Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery

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Abstract

The two species of tiger prawn (*Penaeus semisulcatus* and *P. esculentus*) harvested in Australia's Northern Prawn Fishery are assessed by fitting a Deriso–Schnute delay-difference model to catch and effort data. The population dynamics model has a weekly time-step and allows for week-specificity in recruitment, spawning, availability and fishing mortality. The stock–recruitment relationship is fitted assuming temporally correlated environmental variability and by downweighting recruitments that are poorly determined by the catch and effort data. Uncertainty is quantified through sensitivity tests, variance estimation and future projections. The projections account for the technical interaction between the two species in that effort directed at one species leads to some mortality on the other species. Recruitment and spawning stock size are robustly estimated to have declined substantially but the status of the resource relative to MSY-based reference points is uncertain. The three factors to which the results are most sensitive are the value assumed for the catchability coefficient, the rate of change over time in fishing efficiency, and the future within-year effort distribution. Seasonal closures are shown to lead to increased yields at similar levels of risk to the resource, particularly for *P. semisulcatus*.

Keywords: Tiger prawns; Stock assessment; Delay-difference model; Stock–recruitment; Catchability; Sensitivity

1. Introduction

The Northern Prawn Fishery (NPF) is the most valuable fishery managed by the Australian Commonwealth Government through its statutory body the Australian Fisheries Management Authority (AMFA). The NPF is managed using input controls in the form of limited entry, gear restrictions, and time and spatial closures. Management of this fishery has recently moved from a system of tradeable vessel units (vessel engine power and hull size) to a system of gear units (headrope length). The NPF is based on three prawn species groups (banana, tiger and endeavour prawns), each of which includes at least two species.

Compared with tiger and endeavour prawns, common banana prawns (*Penaeus merguiensis*) appear to be more heavily influenced by the environment than by fishing pressure (Vance et al., 1985; Die and Ellis, 1999). Therefore, quantitative stock assessments are not conducted for these species at present. Although endeavour prawns (*Metapenaeus endeavouri*

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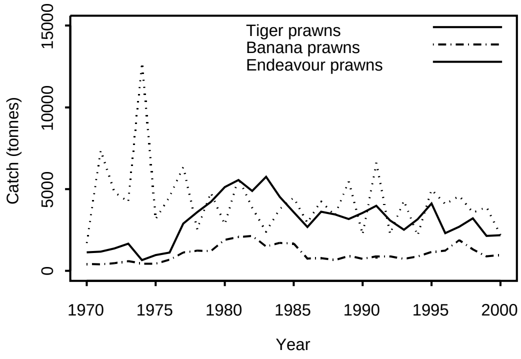

Fig. 1. Catch series (1970–2000) for the three groups of prawn species in the Northern Prawn Fishery.

and *M. ensis*) constitute a significant proportion of the catch in the NPF in recent years (Fig. 1), there are currently insufficient data on which assessments for these species could be based. Tiger prawns (*Penaeus semisulcatus* and *P. esculentus*), on the other hand, have been the focus for quantitative assessments for many years (Somers, 1990; Wang and Die, 1996; Somers and Wang, 1997) and have even been shown to be prone to recruitment overfishing (Wang and Die, 1996; Die et al., 2000). Excessive fishing effort during the 1980s led to an estimated decline in the size of the tiger prawn spawning stock, which was only halted through large, controversial and costly reductions in fishing effort. These reductions were achieved through a combination of licence buy-backs, proportional licence surrenders, additional seasonal closures and bans on daylight fishing (Wang and Die, 1996).

Assessments of the two tiger prawn species are complicated for several reasons: very high natural mortality implies that only a small proportion of prawns survive a year, availability to the fishery changes during the year (Hill and Wassenberg, 1985; Somers and Kirkwood, 1991), the catch is not divided to species in logbooks, and the only information available for determining the values for the parameters of the assessment model is a time-series of catch-rate data for the entire history of the fishery. Information from surveys (e.g. Somers, 1994) and about the length–composition of the catch is available for some years and areas of the fishery. However, the latter are not available over a sufficiently long period and wide spatial extent for use in an assessment model. The commercial length–frequency information, although potentially informative about fishing mortality, is not currently in a form that is amenable to inclusion in the stock assessment.

The Northern Prawn Management Advisory Committee (NORMAC) is responsible for the provision of advice on species caught within the NPF to AFMA and agreed that the key operational management objective for the NPF is to set the level of fishing effort to that level, E_{MSY}, at which maximum sustainable yield (MSY) is achieved, with the underlying assumption that this will lead to the spawning stock being on average at the level at which MSY is achieved, S_{MSY}. Assessments are conducted annually by the Northern Prawn Fishery Assessment Group (NPFAG), which consists of scientists, managers and fishers. Ideally, the effort in the fishery would be adjusted annually to reflect changes to the estimate of E_{MSY} and the impact of changes over time in fishing efficiency (fishing power). Such changes are known to have occurred throughout the history of the fishery (Buckworth, 1985; Robins et al., 1998; Bishop et al., 2000), although the magnitude of change in fishing power constitutes a key uncertainty.

This paper outlines the approach currently used to assess the two tiger prawn species. Emphasis is placed on examining the uncertainty associated with the predictions through sensitivity analyses (changing the assumptions of the assessment model and the values assumed for some of its parameters), estimation of variance, and future projections. This paper extends the assessment framework developed by Wang and Die (1996), who conducted the first assessment of the two tiger prawn species using a fully age-structured model. The future projections represent the first attempt to use models to make dynamic predictions for tiger prawns that consider recruitment variability and serial correlation about the stock–recruitment function.

Although the indices of spawning stock size and recruitment are estimated independently for each species, estimation of the MSY-based reference points, S_{MSY} and E_{MSY}, and the future projections allow for technical interactions between the two species, in that effort directed at one species leads to some mortality on the other species.

2. Methods

The assessment relies on the use of the information on fishing mortality and recruitment contained in the within-season catch-rate dynamics. The calculation of the quantities of interest to management involves a three-step process:

- Estimation of indices of spawning stock size and recruitment using a delay-difference model.
- Estimation of the parameters of a Ricker stock–recruitment relationship based on the output from this model.
- Estimation of MSY, E_{MSY}, and S_{MSY}.

The indices of spawning stock size and recruitment are estimated separately from the parameters of the stock–recruitment relationship. This is, inter alia, to avoid assumptions about the form of the stock–recruitment relationship and the extent of variation and inter-annual correlation in the residuals about that relationship impacting the estimates of spawning stock size and recruitment.

2.1. Estimation of spawning stock size and recruitment

The approach used to estimate the time-series of historical recruitment and the indices of spawning stock size is based on a variant of the delay-difference model developed by Deriso (1980) and Schnute (1985). The model operates on a weekly time-step[1] and allows spawning and recruitment to the fishable population to occur each week. Allowance is also made for weekly changes in availability. Although the model does not explicitly consider the age-structure of the population unlike the model developed by Wang and Die (1996), this is not relevant because recruitment and maturity are reasonably assumed to occur at the same size/age.

The following sections outline the model for a given species and how the values for its free parameters are estimated. For ease of presentation, the equations below ignore the dependence on species.

2.1.1. Basic population dynamics

The dynamics of the recruited biomass and recruited numbers are governed using the equations:

$$\begin{aligned} B_{y,w+1} &= (1+\rho)B_{y,w}\,\mathrm{e}^{-Z_{y,w}} - \rho\,\mathrm{e}^{-Z_{y,w}} \\ &\quad \times (B_{y,w-1}\,\mathrm{e}^{-Z_{y,w-1}} + W_{k-1}\alpha_{w-1}R_{\tilde{y}(y,w-1)}) \\ &\quad + W_k\alpha_w R_{\tilde{y}(y,w)} \quad \text{and} \quad \tilde{N}_{y,w+1} \\ &= \tilde{N}_{y,w}\,\mathrm{e}^{-Z_{y,w}} + \alpha_w R_{\tilde{y}(y,w)} \end{aligned} \tag{1}$$

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

$$Z_{y,w} = M + F_{y,w} \tag{2}$$

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

$$\tilde{y}(y,w) = \begin{cases} y & w < 40 \\ y+1 & \text{otherwise} \end{cases} \tag{3}$$

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

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

The fishing mortality during week w of year y on one of the two tiger species, $F_{y,w}$, includes contributions from targeted fishing on that species as well as from fishing on the other tiger prawn species, changes over time in fishing efficiency, and changes over the year in availability:

$$F_{y,w} = \tilde{q}A_w q_{y,w}\left(E^{\mathrm{T}}_{y,w} + \frac{E^{\mathrm{B}}_{y,w}}{q_b}\right) \tag{4}$$

[1] The weekly time-step is needed given the high natural mortality, high growth rate, and, particularly in recent years, short fishing season. Shorter time-steps (e.g. days) might be desirable to better capture the underlying dynamics of the resource but the basic catch and effort data cannot be extracted at this level of temporal resolution.

$E^{\mathrm{T}}_{y,w}$ is the effort during week w of year y 'targeted' towards the species under consideration, $E^{\mathrm{B}}_{y,w}$ the 'by-catch' effort during week w of year y (the effort targeted at the other tiger prawn species), $\tilde{q}$ the overall catchability coefficient (i.e. the catchability coefficient for the first week of 1993), q_b the by-catch catchability (the number of days of by-catch effort that is equivalent to a single 'targeted' effort day), A_w the relative availability during week w, $q_{y,w}$ the relative efficiency during week w of year y:

$$q_{y,w} = (\omega_y)^{(w-1)/52} \frac{\prod_{y'<y} \omega_{y'}}{\prod_{y''<1993} \omega_{y''}} \tag{5}$$

where ω_y is the efficiency increase during year y.

The value for the overall catchability coefficient, $\tilde{q}$, was estimated using data for 1993 (Wang, 1999) and hence applies to 1993. As a result, Eq. (5) is defined so that fishing efficiency is 1 at the start of 1993 (hence the division by the term $\prod_{y''<1993} \omega_{y''}$).

Specification of the values for the ω_y is difficult. It is clear to all participants in the fishery that 1 day's fishing in the last decade of the 1990s when boats were modern and possessed the latest technical equipment is much more efficient (i.e. leads to larger fishing mortality) than 1 day's fishing in 1970. However, the exact nature (and to some extent magnitude) of the change in efficiency is uncertain. Therefore, two alternative scenarios for how fishing efficiency may have changed over time (a constant rate and year-specific rates) are considered in the assessments (Fig. 2).

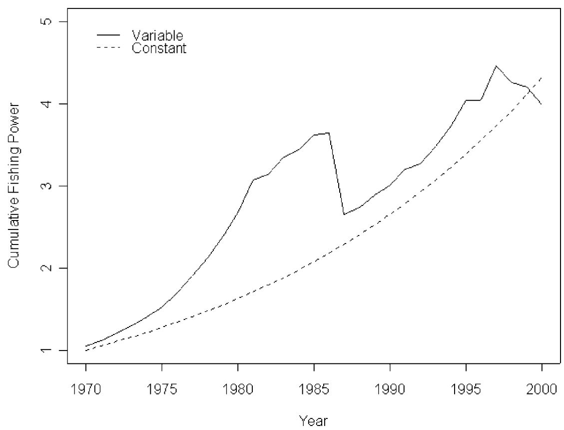

Fig. 2. Two alternative fishing power time-series. The base-case corresponds to a constant 5% rate of increase in fishing power.

Sensitivity tests also examine the impact of different (yet plausible) levels of change over time in efficiency. The two scenarios in Fig. 2 were selected by NORMAC and NPFAG based on analyses of catch-rate data, information on changes of over time in vessel design, information on changes in regulations regarding nets, and comments by commercial fishers. For example, the 5% figure is based, in part, on an analysis of changes in the amount of net trawled by each boat over the early years of the fishery (Buckworth, 1985), and measurements of the impact of the introduction of GPS and plotters from 1988 to 1992 (about 2.5% per annum) based on analyses of catch-rate data (Robins et al., 1998; Bishop et al., 2000).

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

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

where β_w is a relative measure of the amount of spawning during week w.

2.1.2. The likelihood function

The values for the bulk of the parameters of the model are assumed known based on auxiliary information (Table 1). The values for the parameters that are not pre-specified (i.e. the annual recruitments for 1970–1999) are obtained by minimising an objective function involving the catch-in-weight data. Assuming that some function of observed catch-in-weight is normally distributed, the objective function is

$$L = \sum_y \sum_w \{log\, \sigma_{\mathrm{c}} + \frac{1}{2\,\sigma_{\mathrm{c}}^2}[k(Y^{\mathrm{obs}}_{y,w}) - k(Y_{y,w})]^2\} \tag{7}$$

where σ_{c} is the residual standard deviation, $Y^{\mathrm{obs}}_{y,w}$ the observed catch (in weight) during week w of year y, $Y_{y,w}$ the model estimate of the catch (in weight) during week w of year y:

$$Y_{y,w} = \frac{F_{y,w}}{Z_{y,w}} B_{y,w}(1-\mathrm{e}^{-Z_{y,w}}) \tag{8}$$

$k(\,)$ is the transformation function (logarithm, square root and identity).

The summations in Eq. (7) are restricted to the weeks for which the catch is non-zero. Sensitivity to the choice of transformation function is examined because different transformation functions give different

Table 1
The values assumed for the parameters of the population dynamics model that are based on auxiliary information (source (unless stated otherwise): Dichmont et al., 2001)

Quantity	Value	Major data source
Relative weekly recruitment, α_w	Fig. 3a	Monthly survey data spanning several years
Relative weekly spawning, β_w	Fig. 3b	Monthly survey data spanning several years
Relative weekly availability, A_w	Fig. 3c	Survey data for *P. semisulcatus*; experimental and survey data for *P. esculentus*
Overall catchability, $\tilde{q}$	0.000088	1993 catch and effort data (Wang, 1999)
By-catch catchability, q_b	11.11 (*P. esculentus*), 8.26 (*P. semisulcatus*)	Catch and effort data (Somers and Wang, 1997)
Annual efficiency increase, ω_y	Fig. 2	Selected by the assessment group
Length-at-recruitment	Males: 26 mm, females: 28 mm	Survey data (Wang and Die, 1996)
Brody growth coefficient, ρ	0.982 (*P. esculentus*), 0.979 (*P. semisulcatus*)	Tagging data (Kirkwood and Somers, 1984; Somers and Kirkwood, 1991)
Weight-at-recruitment, W_k	18.4 g (*P. esculentus*), 16.5 g (*P. semisulcatus*)	Tagging data (Kirkwood and Somers, 1984; Somers and Kirkwood, 1991)
Weight the week prior to recruitment, W_{k-1}	17.4 g (*P. esculentus*), 15.1 g (*P. semisulcatus*)	Tagging data (Kirkwood and Somers, 1984; Somers and Kirkwood, 1991)
Rate of natural mortality, M	0.045 per week	Tagging data and literature from other fisheries (Wang and Die, 1996)

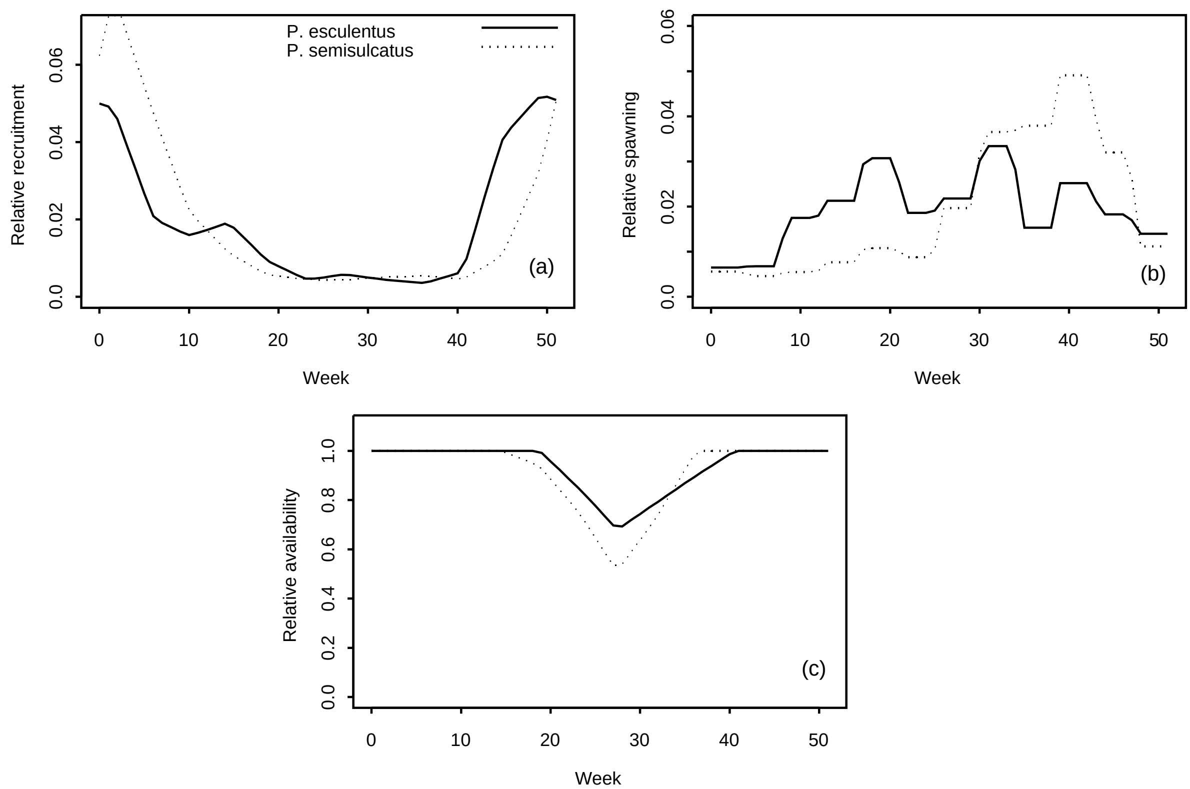

Fig. 3. Within-year patterns of recruitment, spawning and availability for the two tiger prawn species.

emphasis to small and large catches-in-weight. For example, assuming an identity transformation function gives considerable weight to fitting the data for weeks during which the catch is large, whereas assuming a logarithm transformation function gives increased weight to weeks during which the catch is relatively small.

The recruitment in the first year (1969/1970) is assumed to be same as that in the second year (1970/1971), while the recruitment for the last year (2000/2001) is fixed to be equal to that for 1999/2000. The former assumption is made because there are no catches for 1969, so the 1969 recruitment is essentially non-estimable. However, it is needed so that population age-structure for 1970 can be initiated. Given the high natural mortality rate, the results are insensitive to this assumption. The 2000/2001 recruitment is not an estimable parameter of the model because the data for 2000 provide very little information about the magnitude of this recruitment. This is due to the fact that only a small fraction of the 2000 fishery occurred after October (when the 2000/2001 year-class first recruited to the fishery).

2.1.3. Calculating the catch and effort by week and species

Survey work (mainly in the Gulf of Carpentaria; see, for example, Somers (1994) and references therein) suggests that the tiger prawn species at a particular location is determined primarily by the substrate. However, lack of detailed information on substrate, the reporting of catches in logbooks at a fairly coarse spatial scale (the $6' \times 6'$ grid in which most of the night's fishing was done[2]), spatial variability in substrate type, and the fact that hauls may cover a very large area, imply that splitting the catch to species is non-trivial. The approach used in this paper to split the catch by $6' \times 6'$ grid to species was proposed by Somers and Wang (1997). It assumes that the species split for a given grid in the NPF is time-invariant:

1. Calculate a relative split, by weight, for each species for all grid squares included in the surveys.
2. If a logbook catch is ascribed to a $6' \times 6'$ grid for which a survey-based split proportion estimate is available, partition the catch using that estimate.
3. In other cases, use the split proportions for the geographically nearest grid for which a survey-based proportion estimate is available.

This approach does not assume the $6' \times 6'$ grids are homogeneous in substrate composition. Rather, it assumes that logbook records ascribed to any particular grid correspond to sets of trawls that, on average, cover similar territory with respect to their substrate composition.

2.2. Fitting the stock–recruitment relationship

The recruitment for biological year $y+1$ is assumed to be related to the spawning stock size for (calendar) year y, S_y (see Eq. (6)) according to a Ricker[3] stock–recruitment relationship:

$$\hat{R}_{y+1} = \tilde{\alpha} S_y \, \mathrm{e}^{-\tilde{\beta} S_y} \tag{9}$$

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

The relationship between the actual recruitment and the conditional mean based on the stock–recruitment relationship is given by

$$R_y = \hat{R}_y \, \mathrm{e}^{\eta_y}, \qquad \eta_{y+1} = \rho_{\mathrm{r}} \eta_y + \sqrt{1-\rho_{\mathrm{r}}^2}\,\xi_{y+1}, \quad \xi_{y+1} \sim N(0; \sigma_{\mathrm{r}}^2) \tag{10}$$

where ρ_{r} is the environmentally driven temporal correlation in recruitment, and σ_{r} the (environmental) variability in recruitment about the stock–recruitment relationship.

Estimation of the four parameters of the stock–recruitment relationship ($\tilde{\alpha}$, $\tilde{\beta}$, ρ_{r} and σ_{r}) involves minimising the following objective function:

$$L = \log\left(\sqrt{\det(\Omega + V)}\right) + \frac{1}{2}\sum_{y_1}\sum_{y_2} (\log R_{y_1} - \log \hat{R}_{y_1})([V+\Omega]^{-1})_{y_1,y_2}(\log R_{y_2} - \log \hat{R}_{y_2}) \tag{11}$$

[2] Up to 1400 $6' \times 6'$ grids have been fished in a given year.

[3] Results (not shown here) indicate that the estimates of MSY, E_{MSY} and S_{MSY} are insensitive to whether recruitment is related to spawner stock size according to the Beverton–Holt or Ricker stock–recruitment relationships (Dichmont et al., 2001; Table 2).

where Ω represents the temporal correlation among recruitments due to environmental fluctuations.

The entries in the matrix Ω are determined from the assumed autocorrelation structure in recruitment (see Eq. (10)) which implies that the correlation between the recruitments for years y_1 and y_2 is $\rho_r^{|y_1-y_2|}$, i.e. the entries in the Ω matrix are $\sigma_r^2\rho_r^{|y_1-y_2|}$. The V matrix is the (asymptotic) variance–covariance matrix obtained by fitting the population dynamics model (Eqs. (1)–(8)) to the catch and effort data. The estimation of the stock–recruitment relationship therefore takes account of the relative precision of the annual recruitments (through the matrix V) and the impact of (correlated) environmental variability in recruitment (through the matrix Ω).

2.3. Estimation of E_{MSY}

The calculation of E_{MSY} and MSY for each of the two species is based on the assumption of deterministic dynamics (i.e. no variation in recruitment about the stock–recruitment relationship). The annual catch is equal to the long-term catch from an annual cohort under this assumption.

E_{MSY} is assumed to be different for *P. semisulcatus* and *P. esculentus* although E_{MSY} cannot be estimated separately for each species because, through Eq. (4), targeted fishing for *P. semisulcatus* implies some fishing mortality on *P. esculentus* and vice versa. Therefore, E_{MSY} (and consequently MSY and S_{MSY}) are obtained by maximising the sum of the catches of the two species. Simply summing the catches of the two species when defining MSY is appropriate in this case because the price is independent of species.

The equilibrium catch for one of the species from an annual cohort as a function of the total annual effort targeted on the two species, $C(E)$, is computed as $C(E) = \tilde{C}(E)R(E)$, where $\tilde{C}(E)$ is the equilibrium catch as a function of effort when the annual recruitment is 1 and $R(E)$ is the equilibrium level of recruitment as a function of effort. The value for $\tilde{C}(E)$ is determined by projecting the population dynamics model (Eq. (1)) forward for 10 years under the assumption that recruitment is unity (i.e. $R_y = 1$) in the first year and then zero thereafter. The choice of 10 years is to ensure that (essentially) all prawns are dead by the end of the projection period. The value of $\tilde{C}(E)$ is determined by summing the catch in weight (see Eq. (8)) over time. A by-product of the 10-year projection is the spawning index (per recruit) as a function of effort, $\tilde{S}(E)$. Recruitment as a function of effort is computed from the stock–recruitment relationship (see Eq. (9)), replacing S_y and R_y by $R(E)\tilde{S}(E)$ and $R(E)$, respectively, and solving for $R(E)$. For the Ricker stock–recruitment relationship this leads to

$$R(E) = \frac{\log(\tilde{\alpha}S(E))}{\tilde{\beta}S(E)} \tag{12}$$

It is necessary to specify the within-year pattern of effort in order to calculate $\tilde{C}(E)$ and hence E_{MSY} and MSY. This pattern has changed over the history of the fishery due to changes to the management regulations, such as the introduction of a mid-year spawning closure and a seasonal closure over the December/January period. The base-case assumption of this paper is that the average pattern of effort over the years 1993–2000 provides the ‘best’ appraisal of the future within-year distribution of effort.

2.4. Representing uncertainty and conducting projections

The uncertainty associated with the values for the parameters of the population dynamics model can be determined from the asymptotic variance–covariance matrix obtained by inverting the Hessian matrix. It is, however, also necessary to have a set of alternative vectors of model parameters in order to conduct the projections and to compute the variances of quantities that are functions of the parameters. These vectors are generated from the variance–covariance matrix assuming that the parameters are normally distributed.[4]

The projections involve pre-specifying the future time-series of fishing effort (both target and by-catch effort, and split to week) and projecting from the final year of the assessment (2000) for the pre-specified number of years. Each simulation involves the following steps:

(a) Select a set of values for the model parameters.
(b) Project the population from 1969 until the last year of the assessment (2000).

[4] This approach is referred to as the ‘numerical delta’ method by Patterson et al. (2001).

(c) For each year, y, from the last year of the assessment until the final year of the projection:
   (i) generate a recruitment residual for biological year $y+1$, η_{y+1} (see Eq. (10));
   (ii) project the model from the start to the end of year y for different choices of R_{y+1} until the equation $R_{y+1} = \tilde{\alpha} S_y \, e^{-\tilde{\beta} S_y} \, e^{\eta_{y+1} - \sigma_r^2/2}$ is satisfied.

Note that step (c) overrides the fixed recruitment for 2000.

3. Results and discussion

The results from the stock assessment are voluminous (e.g. recruitment numbers by week), and need to be summarised further. For the purposes of this paper, the results are summarised by the four quantities of greatest interest to the decision makers:

(a) Steepness: the expected recruitment at 20% of the virgin spawner stock size (Francis, 1992).
(b) The ratio (expressed as a percentage) of the spawner stock index for 2000 to S_{MSY} (abbreviation 'S_{2000}/S_{MSY}').
(c) MSY: the (deterministic) maximum sustainable yield.
(d) E_{MSY}: the effort level at which MSY is achieved.

The steepness of the stock–recruitment relationship is reported as it indicates the relative productivity of the resource. S_{2000}/S_{MSY} and E_{MSY} are quantities that relate to the current management objectives for the fishery (values for S_{2000}/S_{MSY} less than 100% indicate over-exploitation, while employing a fishing effort equal to E_{MSY} is a current management objective for the fishery). For consistency with the definition of fishing power (see Eq. (5)), E_{MSY} is expressed in terms of 1993 days.

3.1. Choice of transformation function for the catch-in-weight data

The assessments conducted by Wang and Die (1996) assumed the errors in catch-in-weight were independent of the size of the catch-in-weight (i.e. the function $k(\,)$ in Eq. (7) was set to the identity function). However, this choice of transformation function leads to somewhat non-normal error distributions (Fig. 4). In contrast, assuming that the square root of the catch-in-weight is normally distributed removes this problem (Fig. 4). The remaining analyses of this paper are consequently based on the square root transformation.

3.2. The base-case analyses

The base-case analyses use the square root transformation when fitting to the catch-in-weight data and assume a 5% annual constant increase in fishing power (Fig. 2; 'constant'). Fig. 5 shows the time-trajectories for recruitment and spawning stock size (with 90% confidence intervals) and Fig. 6 shows the fit of the Ricker stock–recruitment relationship to the spawning stock size and recruitment data for the base-case analyses. The time-series of spawning stock size and recruitment are both one-way trips (essentially continuous declines in spawning stock size and recruitment with some stability in the most recent years). The patterns of recruitment are mimicked in those of spawner stock size because, given the high rate of natural mortality, the bulk of the spawner stock size for a particular calendar year consists of the recruits from the previous year.

Fig. 5 shows that the uncertainty associated with the estimates of recruitment is greatest for the earliest and (to a much lesser extent) the most recent years. This pattern is as expected from results for age-based virtual population analyses (e.g. Butterworth et al., 1990). This uncertainty is taken into account when fitting the stock–recruitment relationship (Eq. (11)), because the poorly determined recruitments are downweighted. It should be noted, however, that the error bars in Fig. 5 almost certainly underestimate the true extent of uncertainty because the analyses on which Fig. 5 are based involve fixing many of the parameters based on auxiliary information and ignoring among-year variation in availability, recruitment and spawning. The estimates of steepness (e.g. 0.302 and 0.271 for *P. esculentus* and *P. semisulcatus*, respectively) are low compared to estimates of steepness for teleost fish species (e.g. Myers et al., 1999). This is particularly surprising given that the time-series nature of the stock and recruitment data is likely to lead to positively biased estimates of steepness (Walters, 1985).

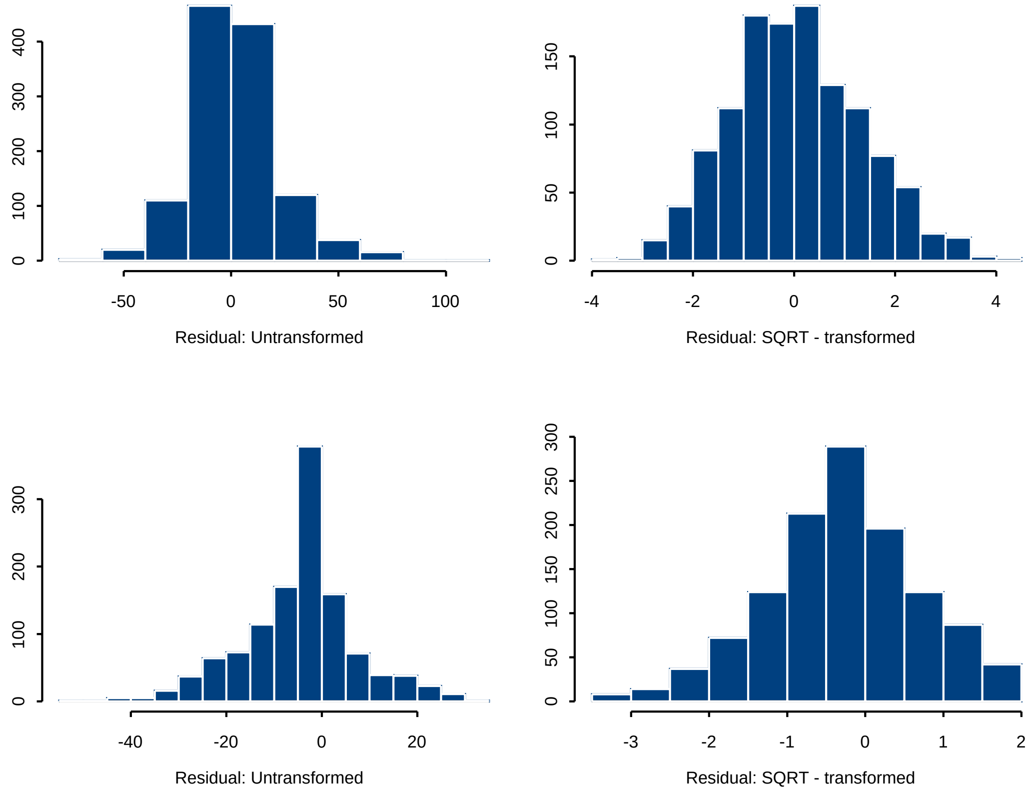

Fig. 4. Residuals about the fits to the catch-in-weight data for *P. esculentus* and *P. semisulcatus* (upper and lower panels, respectively). Results are shown in the left panels when the untransformed catches-in-weight are assumed to be normally distributed and in the right panels when the catches-in-weight after square root transformation are assumed to be normally distributed.

3.3. Assessment sensitivity tests

An extensive examination of sensitivity was conducted (Dichmont et al., 2001; Table 2). The results from the assessments were, however, highly sensitive to only three factors: the assumed value for the overall catchability coefficient, the assumed rate of efficiency increase, and the fishing effort pattern used to calculate the yield per recruit.

3.3.1. The overall catchability coefficient

The base-case and all previous assessments have assumed (rather than estimated) the value for the overall catchability coefficient. Fig. 7 shows a likelihood profile for this parameter. Somewhat unexpectedly, the best fits to the data occur for very low values for the overall catchability coefficient (corresponding to an essentially infinite population size). However, the relationship between recruitment and spawner stock size becomes increasingly linear (a value for steepness closer to 0.2) as the assumed value of the overall catchability coefficient is reduced (Fig. 7, upper right panel). Values for steepness of 0.2 are, however, unrealistic as they imply no surplus production. The ratio of current effort to E_{MSY} is largely independent of the overall catchability coefficient although this is not the case for the ratio $S_{2000}/S_{\mathrm{MSY}}$.

Ye (2000) overviews the information on stock and recruitment for a range of short-lived prawn species. The estimates of steepness for tiger prawns implied by the data in Ye (2000) range from 0.2 to 0.8. This range would suggest that values for catchability lower than that in Table 1 are probably implausible. In principle, the information in Ye (2000) could be included more formally in the assessment through some sort of penalty function (or prior) on steepness. However,

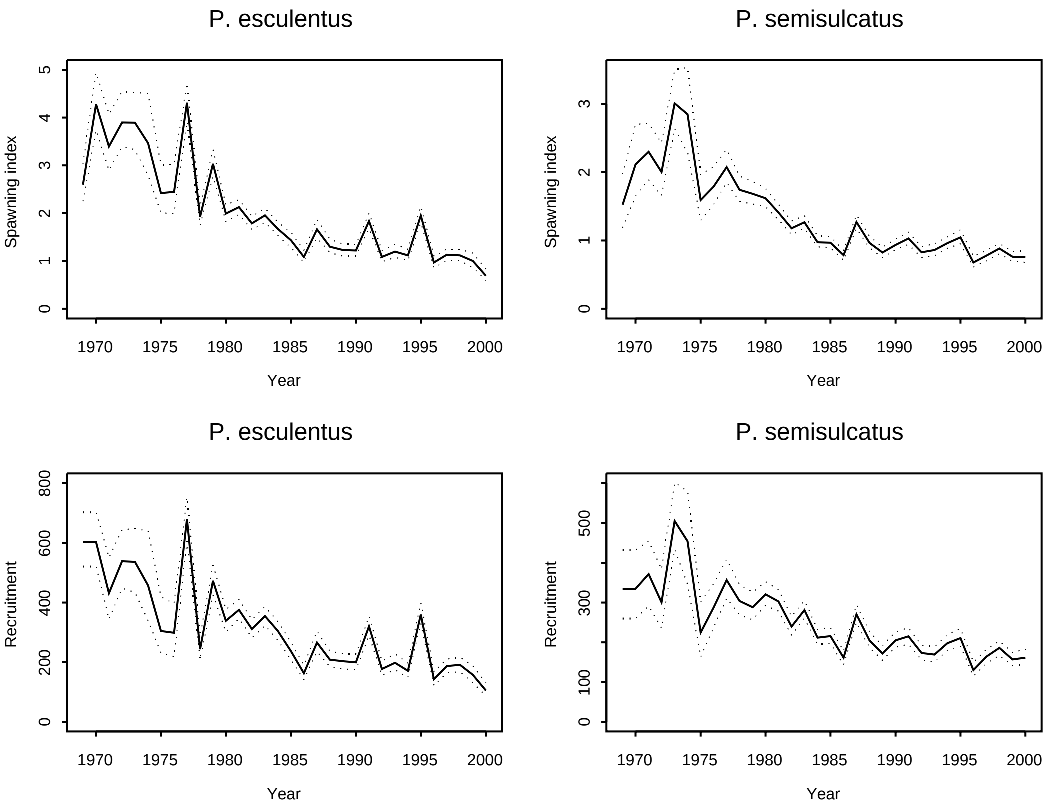

Fig. 5. Medians and 90% confidence intervals for the time-trajectories of spawning stock size and recruitment for the base-case analyses.

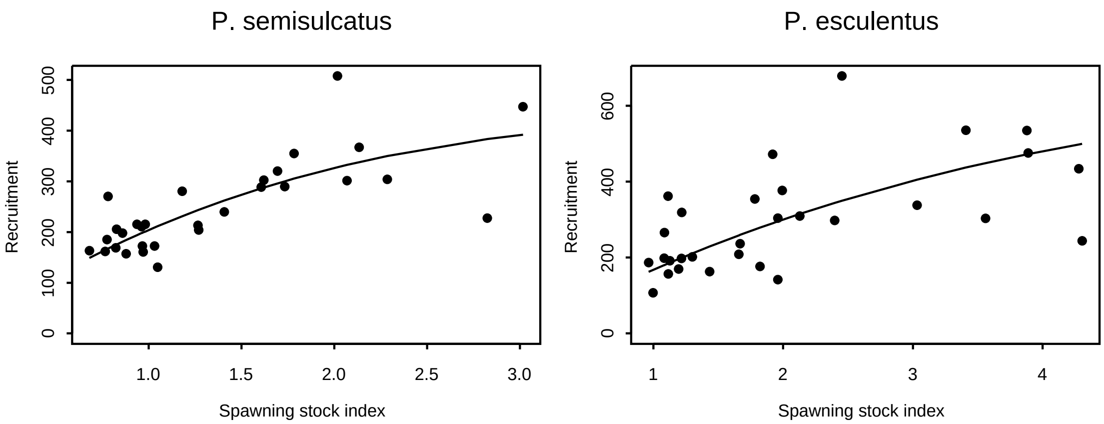

Fig. 6. The stock–recruitment relationships for the base-case analyses.

Table 2
Overview of the sensitivity tests[a]

Sensitivity test	Impact on MSY and E_{MSY}	Impact on recruitment and depletion
Recruitment pattern		
Earlier by 1 month	Low	Low
Later by 1 month	Low	Low
Overall catchability coefficient	High	Low
Annual efficiency increase	High	High
Within-year availability pattern estimated with a sine function	Better fits, but model does not produce sensible parameter estimates	
Brody growth coefficient	Low	Low
Shape of the stock–recruitment relationship (Ricker or Beverton–Holt)	Low	Low
Within-year fishing pattern (future)	High	N/A
Transformation of catch in the likelihood function (square root, logarithm or unity)	Low	Medium
Input data uncertainty included[b]	Low	Low
Process error in natural mortality[b]	Low	Low
Process error in weekly recruitment pattern[b]	Low	Low
Process error in catchability[b]	Low	Low
Process error in catch-at-age[b]	Low–medium	Low–medium
Error in species distribution and division[b]	Low	Low

[a] Columns 2 and 3 provide a qualitative summary of the impact of the sensitivity test.
[b] See Dichmont et al. (2001) for the technical specifications for these sensitivity tests.

such inclusion is beyond the scope of the present assessment. The high steepness values reported by Ye (2000) were estimated in one area only and using survey and commercial logbook data, while the lower values tended to be based on commercial data only which may suggest that the information in Ye (2000) is insufficient to develop penalty functions or priors.

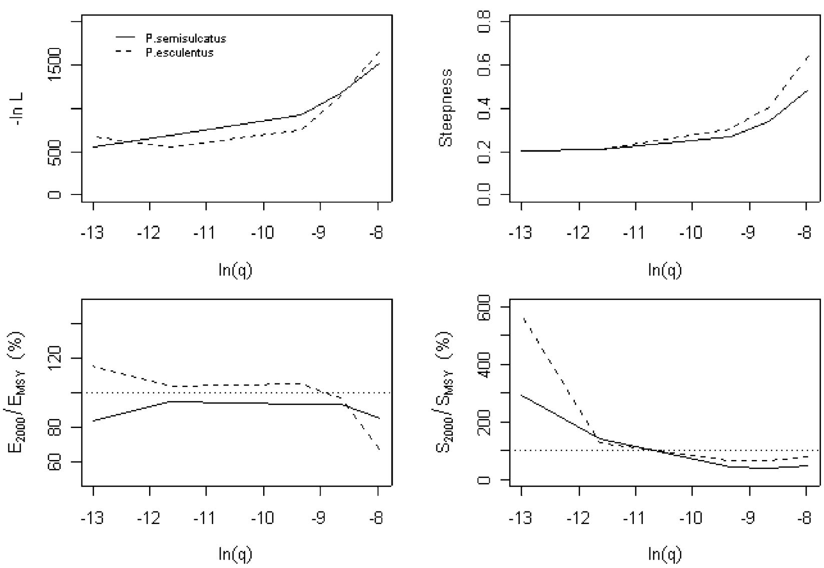

Fig. 7. The negative of the logarithm of the likelihood function, steepness, E_{2000}/E_{MSY}, and S_{2000}/S_{MSY} as a function of the assumed value for the logarithm of the overall catchability coefficient.

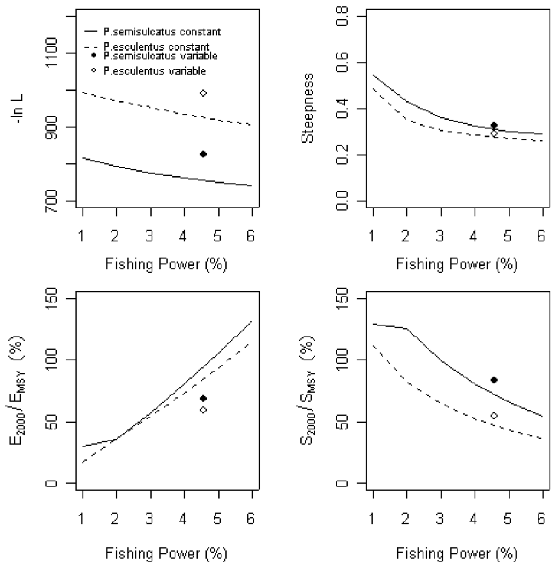

Fig. 8. The negative of the logarithm of the likelihood function, steepness, $E_{2000}/E_{\mathrm{MSY}}$, and $S_{2000}/S_{\mathrm{MSY}}$ as a function of the rate of efficiency increase. The solid dots denote the results for the 'variable' option in Fig. 2.

3.3.2. Fishing power

The base-case analysis and all previous assessments have been based on the assumption that fishing power has been increasing at a fixed percentage each year. The base-case percentage is 5% ('constant' in Fig. 2) and sensitivity has been explored in the past to alternative constant rates of fishing power increase (e.g. Wang and Die, 1996). Recently, the assumption of constancy has been questioned given the known history of changes in technology and regulations in the fishery (Northern Prawn Fisheries Assessment Group, pers. commun.), resulting in the creation of an alternative time-sequence of changes in fishing power ('variable' in Fig. 2).

The results are very sensitive to assumptions about changes over time in fishing efficiency (Fig. 8). As expected, the results become more pessimistic (lower values for steepness, $S_{2000}/S_{\mathrm{MSY}}$ and higher values for $E_{2000}/E_{\mathrm{MSY}}$) with higher (assumed) values for the constant rate of efficiency increase. The results are also sensitive to how changes in fishing efficiency have occurred (contrast the results for the 'variable' scenario in Fig. 8 (an annual geometric mean increase of about 4.6%) with those for a constant rate of increase of 5%). The reason for the sensitivity in this case is that a major decline in fishing power is assumed to have occurred in 1987 under the 'variable' scenario, and the subsequent low annual fishing power increase over the last 5 years (see Fig. 2) is predicted to have resulted in some resource recovery. The constant 5% and 'variable' scenarios differ to the greatest extent in terms of $E_{2000}/E_{\mathrm{MSY}}$ (due to differences in E_{2000} rather than E_{MSY}). It is also noteworthy that the negative log likelihood is appreciably higher for the 'variable' scenario than for the constant 5% scenario suggesting that the catch and effort data supply some information about the time-sequence of changes in fishing efficiency, although not too much about the overall extent of this change.

3.3.3. Within-year effort distribution

Fishing occurred almost throughout the year during the early 1980s. By 1993, the year in which there was a large-scale buy-back of vessel units, there were mid-year as well as December/January closures. The sensitivity of the results to assuming a uniform distribution of effort is explored in Table 3. The differences between within-year effort distribution scenarios in Table 3 are due only to differences in the estimates of quantities related to MSY because the indices of spawning stock size and recruitment and the parameters of the stock–recruitment relationship are based on the historical catch and effort data for which the within-year distribution of effort is known. Table 3 therefore implicitly examines the benefits of the seasonal closures. MSY and E_{MSY} are both higher for the most recent within-year effort pattern. Therefore, the seasonal closures both reduce fishing mortality and simultaneously increase potential yields.

3.4. Future projections

Fig. 9 shows the trade-off between the probability that S_{2010} exceeds S_{MSY} and the average catch over the years 2001–2010 associated with different total levels of fishing effort (expressed in 1993 days) from 0 (closure) to 40,000 days based on the base-case analysis. The total effort is split to targeted effort by species in the ratio of the base-case point estimates of E_{MSY} for the two species. The within-year fishing effort pattern for these projections is assumed either to be uniform or the average pattern during 1993–2000.

Table 3
Management-related quantities (point estimates and 90% intervals) for variants of the base-case assessment, which modify the assumption regarding the within-year distribution of future fishing effort

Quantity	1993–2000 average		Uniform	
	P. semisulcatus	*P. esculentus*	*P. semisulcatus*	*P. esculentus*
S_{1999}/S_{MSY} (%)	66 (54–81)	43 (31–58)	68 (55–83)	43 (31–58)
MSY (t)	1709 (1449–2022)	1418 (1078–2040)	1496 (1505–1789)	1343 (1020–1932)
E_{MSY} (1993 days)	11041 (8623–14744)	6588 (4709–11388)	6986 (5609–8963)	5527 (4002–9239)

As expected, the probability of being below S_{MSY} in 2010 increases as a function of effort. The results for the best estimate of E_{MSY} are highlighted in Fig. 9 because the present constant effort policy applied to manage tiger prawns in the NPF is based on E_{MSY}. The average catch also increases as a function of effort. However, unlike S_{2010}/S_{MSY}, it reaches a maximum and then declines. This occurs because high levels of effort lead to the resource being driven to low levels. This is counter-balanced to some extent by removal of ‘standing stock’ but only partially. The difference in the risk-reward curves between the uniform and 1993–2000 average effort patterns is much smaller for *P. esculentus* than for *P. semisulcatus*.

There is a distinct difference between the results for *P. semisulcatus* and those for *P. esculentus* in terms of risk and reward. For *P. semisulcatus*, risk rises sharply after an effort of 5000 standardised days. Conversely, for a small decrease in average catch, the risk can be reduced substantially. This is not the case for *P. esculentus*. The risk is already substantially higher at 5000 days than for *P. semisulcatus*. A small reduction in risk results in a similar decrease in catch. This difference may reflect the lower productivity of *P. esculentus*.

There appear to be substantial benefits to be gained by appropriately chosen seasonal closures, especially for *P. semisulcatus*. For this species, there is a large difference between the results for a uniform fishing pattern and those for an effort distribution pattern equal to the average during 1993–2000. The major differences between the two patterns lie in the mid- and end-season closures. The mid-year temporal closure and the fact that little effort is directed towards *P. semisulcatus* in the first part of the year imply that little effort is applied to *P. semisulcatus* prior to spawning. However, this is not the case for *P. esculentus* and

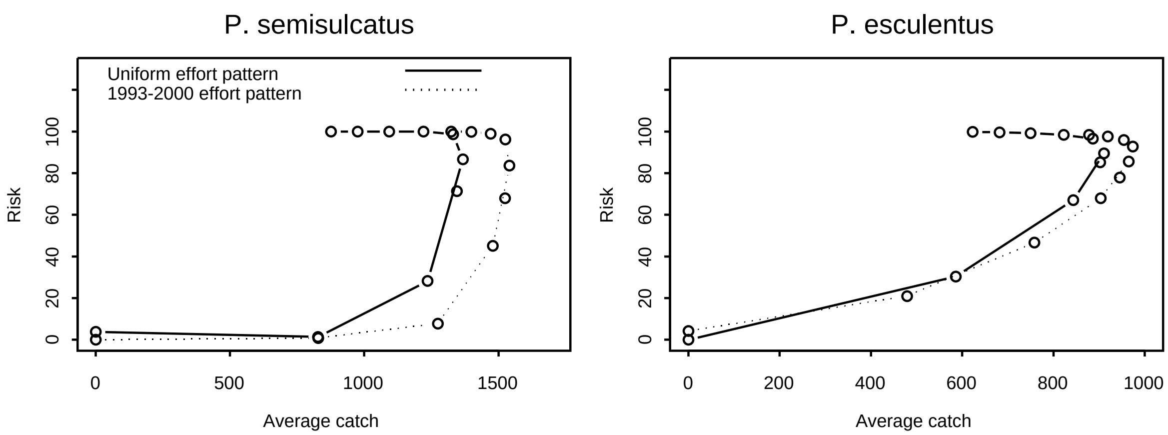

Fig. 9. The probability that S_{2010} exceeds S_{MSY} (“risk”) versus the average catch during 2001–2010. Results are shown for *P. semisulcatus* and *P. esculentus* and for two assumptions regarding the within-year distribution of future fishing effort. The open symbols denote the results corresponding to setting future fishing effort to the current best estimate of E_{MSY}.

therefore much of the effort on *P. esculentus* occurs prior to spawning even with the recent within-year effort pattern.

3.5. General discussion

The approach used to provide management advice for tiger prawns in Australia's Northern Prawn Fishery is based on fitting a population dynamics model to weekly catch and effort data. Assessment approaches based on fitting population dynamics models have formed the basis for management advice for tiger prawns in the NPF for several years (e.g. Wang and Die, 1996; Haddon, 1997). A few prawn resources elsewhere in the world are assessed using fishery-independent as well as commercial catch and effort data (e.g. Quinn et al., 1998), while Caputi et al. (1998) illustrate how it is possible to estimate the stock–recruitment relationship directly from data collected from a fishery. The population dynamics model that underlies the analyses of this paper has been tailored to the specifics of NPF tiger prawns by allowing for week-specificity in recruitment, spawning and availability. The weekly nature of the population dynamics model also enables changes over time in season length to be considered. Table 3 suggests that the results are highly sensitive to the within-year effort distribution pattern and ignoring this when conducting assessments would have led to considerable bias.

The modelling approach adopted for tiger prawns is, however, not without its problems. For example, it is clear from Fig. 7 that catchability, availability, recruitment and fishing-induced mortality cannot be distinguished given catch and effort data alone. These factors could be distinguished, in principle at least, had time-series of catch-at-age data been available. However, this was not the case. The solution adopted in this paper to pre-specify catchability and availability using auxiliary information is therefore necessary but certainly not ideal. The use of time-invariant recruitment, availability and spawning patterns (Fig. 3) is less-than-ideal but is unavoidable in the absence of additional data. The last five sensitivity tests in Table 2 involve assessing the likely impact of uncertainty about the values for parameters assumed known from auxiliary information. These sensitivity tests involved generating values for the fixed parameters of the assessment from subjective priors and re-running the assessment. Replicating this process leads to a distribution of outcomes. However, the widths of these distributions were relatively narrower than those based solely on the uncertainty associated with fitting the model to the data. Although the square root transform improves the normality of the residuals (Fig. 4), within-year patterns in the residuals remain (Fig. 10). Attempts to remove this by postulating different within-year patterns in availability failed as this led to further confounding.

By-catch catchability is included when estimating the annual recruitment and spawning stock indices and when calculating E_{MSY}. The former is relatively standard as it simply reflects accounting for

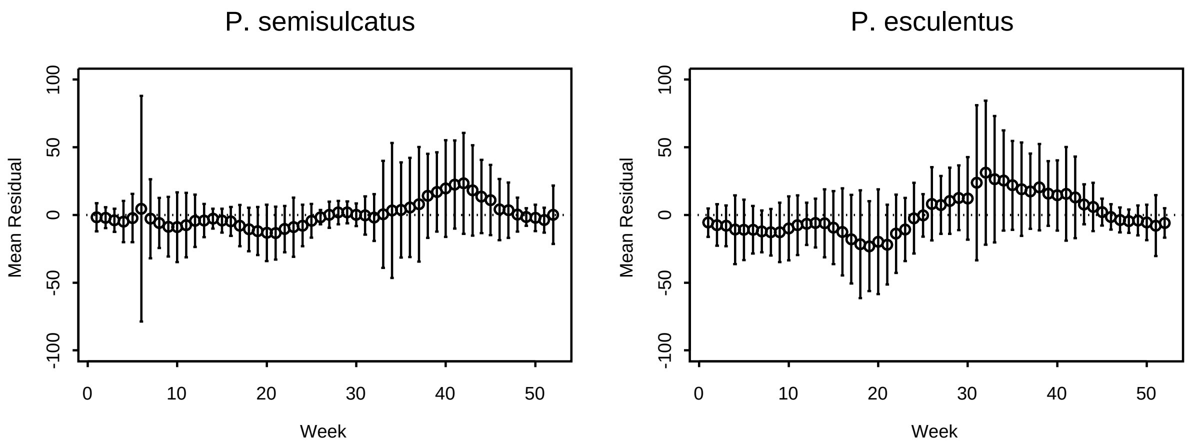

Fig. 10. Within-year residual patterns about the fit to the catch-in-weight data for the base-case analysis.

all known catches. In contrast, the latter is novel, even for assessments of teleosts. Including by-catch catchability when computing E_{MSY} is, however, an important factor for this assessment—ignoring the by-catch catchability when computing E_{MSY} would lead to an over-estimation of the target effort by roughly 10%.

The estimates of the management-related quantities were found to be sensitive to the assumptions about the distribution of effort across the season. The uniform fishing year led to lower estimates for MSY and E_{MSY} than using the average of the pattern during 1993–2000. This result highlights the benefits of reducing effort during key periods in the life cycle of the animal (e.g. spawning and recruitment).

As is often the case, some of the results are robust to uncertainty while others are not. The result which is common to all analyses is that recruitment (and the spawning stock) in recent years is substantially smaller than at the start of the fishery. Unfortunately, the steepness of the stock–recruitment relationship is not well determined by the data, being close to implausibly low when compared with estimates of this parameter for teleosts. Unfortunately, the values for the key management reference points MSY and E_{MSY}, and hence whether the resource should be considered to be over-exploited, are highly sensitive to the shape of the stock–recruitment relationship. Although the bulk of the results point to the qualitative conclusion that both tiger prawn species, particularly *P. esculentus*, are currently over-exploited, the sensitivity of the stock–recruitment relationship to the assumptions underlying the assessments questions the use of MSY-related management quantities and indeed any reference points that rely on the use of a stock–recruitment relationship. One way to identify more appropriate reference points would be through the use of the management strategy evaluation approach (Smith, 1994; Punt et al., 2001).

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