

Management strategies for short-lived species: The case of Australia's Northern Prawn Fishery

1. Accounting for multiple species, spatial structure and implementation uncertainty when evaluating risk

Catherine M. Dichmont^{a,*}, Aijun (Roy) Deng^a, André E. Punt^{b,c},
William Venables^a, Malcolm Haddon^d

^a CSIRO, P.O. Box 76, Cleveland, Qld 4163, Australia

^b School of Aquatic and Fishery Sciences, Box 355020, University of Washington, Seattle, WA 98195-5020, USA

^c CSIRO, GPO Box 1538, Hobart, TAS 7001, Australia

^d MRL/TAFI, University of Tasmania, Private Bag 49, Hobart, TAS 7001, Australia

Received 4 August 2005; received in revised form 8 May 2006; accepted 4 June 2006

Abstract

The Northern Prawn Fishery harvests a variety of prawn species including some short-lived species with highly variable recruitment such as banana prawns and slightly longer-lived tiger prawns with less variable recruitment. An evaluation of stock assessment methods and management strategies for the Northern Prawn Fishery using the management strategy evaluation (MSE) approach requires an (operating) model of the resource to act as the 'truth' for the analyses. A five-stock, two tiger prawn species operating model with a weekly time-step is developed and conditioned using more than 30 years of logbook catch and effort data as well as the results of fishery-independent research. The operating model is projected beyond the present using stock-specific stock–recruitment relationships. Banana prawns are not modelled explicitly, but their impact on the management system is simulated empirically. The input control nature of the management system is mimicked using an effort allocation model that allocates effort by species, area and week. This model allows for the impact of changes over time in efficiency, a key uncertainty in the assessment of these species, and the impact of management implementation error, which has historically been substantial. Some of the properties of the operating model are illustrated by projections based on a constant effort policy.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Input controls; Monte Carlo simulation; Multispecies modelling; Northern Prawn Fishery; Spatial structure

1. Introduction

The precautionary approach to fisheries (FAO, 1996) highlights the need for management systems that can be shown to be robust to the uncertainties inherent in stock assessment and management. It also highlights that the lack of certainty should not prevent implementation of management actions. The tools used for providing fisheries management advice (data collection strategies, analysis methods and decision rules) can be evaluated in terms of their likely ability to satisfy the management objectives using simulation (Kirkwood and Smith, 1996). Simulation (or the management strategy evaluation (MSE) approach) has

been applied extensively for many fisheries at the single- or the multispecies level (Punt, 1992; De la Mare, 1996; Butterworth et al., 1997; Punt and Smith, 1999; Smith et al., 1999; Punt et al., 2002) and, in recent years, for ecosystem objectives (Sainsbury et al., 2000).

The MSE approach (Fig. 1) distinguishes between the true state of the resource (as represented by the 'operating model') and that perceived through data collection strategies and stock assessments (a component of the 'management strategy'). The management strategy includes not only an assessment procedure, but also a decision rule that uses information on the perception of the status of the system to determine management advice. The management advice determines the management actions and hence any impacts these actions have on the resource and the associated fishery. The MSE approach therefore attempts to consider the whole management system. Representation of

* Corresponding author. Tel.: +61 7 3827 7219; fax: +61 7 3826 7222.
E-mail address: cathy.dichmont@csiro.au (C.M. Dichmont).

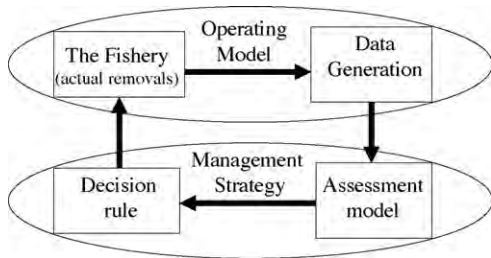


Fig. 1. Conceptual overview of the MSE approach, indicating the key components of the framework.

uncertainty is a key component of the MSE approach, and the impact of several sources of uncertainty can be evaluated. Specifically, many different operating models may be constructed to capture uncertainty about, for example, the true dynamics of the resource, how the data are collected, etc. Some of these operating models can be quite speculative, designed to determine whether factors not currently supported by existing data, but which are nevertheless not implausible, may impact the robustness of management strategies (Butterworth and Punt, 1999).

Most applications of the MSE approach have focused on longer-lived species managed using output controls (e.g. Butterworth et al., 1997; Punt and Smith, 1999; Smith et al., 1999; Punt et al., 2002). In contrast, many of the world’s most valuable fisheries are those for short-lived species managed using input controls. There are several sources of uncertainty that are specific to fisheries managed using input controls and which need to be considered when the MSE approach is used to evaluate management strategies for such fisheries. This paper illustrates how an operating model can be constructed for a fishery that is managed using input controls and targets several species, based on the actual example of evaluating management strategies for the fishery for tiger prawns (*Penaeus semisulcatus* and *Penaeus esculentus*) in Australia’s Northern Prawn Fishery (NPF).

This operating model can be used to evaluate various aspects of a management system for the NPF, including, for example, (a) how different management strategies perform in terms of their ability to satisfy the management objectives (Dichmont et al.,

2006a,b), (b) the advantages and disadvantages of input controls versus output controls and (c) the impact of various uncertainties on the ability of stock assessment methods to provide estimates of quantities such as biomass and MSY. However, owing to space constraints, the examples in this paper are based on evaluating the impact of future levels of fishing effort.

2. Overview of Australia’s Northern Prawn Fishery

The NPF is one of the most valuable fisheries managed by the Australian Commonwealth government. Management is through input controls in the form of limited entry, gear restrictions and time and area closures. Currently, management of this fishery is through a system of tradeable gear units (head-rope length). The NPF is based on three prawn species groups (banana, tiger and endeavour prawns), each of which consists of at least two species (Pownall, 1994; Venables and Dichmont, 2004).

The biological characteristics and harvests of the three species groups differ quite markedly. For example, common banana prawns, *Penaeus merguensis*, are short-lived and appear to be environmentally driven (Die and Ellis, 1999; Vance et al., 1985) while tiger and endeavour (*Metapenaeus endeavouri* and *Metapenaeus ensis*) prawns are longer-lived (a maximum age of about 2 years) and appear to exhibit a relationship between stock size and subsequent recruitment (which implies that they can be recruitment overfished). Red-leg banana prawns, *Penaeus indicus*, and the two species of endeavour prawns, have less variable recruitment and lower natural mortality than common banana prawns, but are shorter-lived and more variable than tiger prawns.

The fishery for prawns in the NPF was first focused on banana prawns, but, thereafter years, catches of banana and tiger prawns have been roughly equal (Fig. 2). Endeavour prawns have not constituted a significant proportion of the total catch. The fishery switches among species during the year. In recent years, the fishery has started in April targeting common banana prawns which are more catchable at that time due to the presence of large aggre-

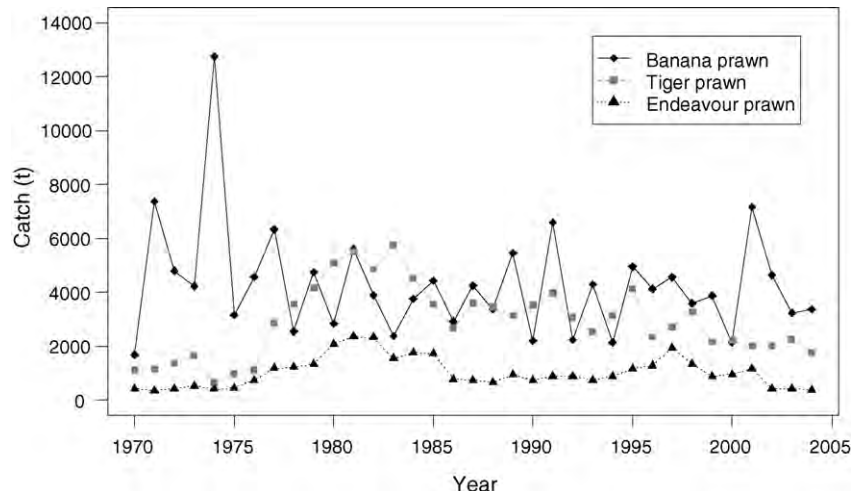


Fig. 2. Annual landings of banana, tiger and endeavour prawns (t).

gations (Die and Ellis, 1999). The fleet switches to tiger prawns for which the catch rate is lower, but less variable, as the abundance of banana prawns drops owing to fishing and natural mortality. In recent years, the fishery has consisted of two subseasons split by a mid-year spawning closure. Red-leg banana prawns are only caught during the second subseason and at neap tides.

Tiger prawns have been the focus for quantitative stock assessments for many years (Somers, 1990; Somers and Wang, 1997; Wang and Die, 1996; Dichmont et al., 2001, 2003a) owing to the perception that these species can be recruitment overfished. Endeavour prawns are predominantly a bycatch of targeting tiger prawns and management measures for tiger prawns therefore also tend to benefit endeavour prawns. The dynamics of common banana prawns appear to be almost completely environmentally driven. Assessments of tiger prawns have shown that excessive fishing effort during the 1980s and 1990s led to a resource decline (Wang and Die, 1996; Dichmont et al., 2003a), that 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, seasonal closures and bans on daylight fishing (Cartwright, 2005).

The primary data sources for tiger prawns in the NPF are log-book catch and effort data, and the results of fishery-independent surveys. The catches, which are not reported by species, can be disaggregated to species fairly reliably using the results from fishery-independent surveys (Venables and Dichmont, 2004). Stock assessment of tiger prawns is, however, complicated for several reasons: high natural mortality implies a low probability of a prawn surviving more than a single year, spawning patterns and availability to the fishery change during the year (Hill and Wassenberg, 1985; Somers et al., 1987; Somers and Kirkwood, 1991), and recruitment is continual throughout the year with a three to 4-month peak (Somers and Wang, 1997; Dichmont et al., 2003a). Furthermore, extensive changes over time in fishing efficiency (fishing power) are known to have occurred throughout the history of the fishery (Buckworth, 1985; Robins et al., 1998; Bishop et al., 2000, 2004; Dichmont et al., 2003b), but the magnitude of the change in fishing efficiency remains a key uncertainty.

Finally, although Dichmont et al. (2001) identified seven potential stocks of tiger prawns in the NPF based on catch and effort data, catchment boundaries, regions of seagrass bed habitat (Poiner et al., 1987; Coles et al., 1989), and the results of oceanographic models (Condie et al., 1999), no genetic data are available to distinguish stocks and hence to determine the correct placement of boundaries among putative stocks. As a result, stock assessments are still at the scale of the entire NPF and consequently ignore the impact of potential (but unknown) stock structuring (Dichmont et al., 2003a,b).

3. The operating model

The operating model is the underlying ‘truth’ being managed and therefore needs to be sufficiently general to be able to capture all key hypotheses related to the dynamics of the resource and its associated fishery (Butterworth and Punt, 1999). In par-

ticular, it needs to be able to capture multiple species and the impact of inputs controls on the dynamics of the fishery. The operating model for the NPF consists of two main components: a biological model component of the focus group, tiger prawns and an effort allocation component. The focus of this section is on the effort allocation component of the operating model because the biological component is virtually identical to the model on which previous assessments have been based (Dichmont et al., 2003a).

Tiger prawns appear to form regional subpopulations that, although not necessarily genetically isolated, do not mix much and need to be managed separately (Die et al., 2001). The biological component of the operating model (see Appendix A for details on the basic dynamics) has a weekly time-step and can represent multiple stocks and several species. The stocks interact through the ‘technical interaction’ that results from fishing for one species leading to catches of other species. However, biological interactions among the species, such as might be predicted through trophodynamics, are ignored. A weekly time-step is adopted to capture the within-year dynamics of the fishery, including how it switches from banana to tiger prawns.

3.1. Effort allocation component of the model

The effort allocation component of the operating model provides the link between the management decisions and the biological component of the operating model. The input for the effort allocation model is the management advice on the total effort of the fleet (in days) to be targeted towards tiger prawns (aggregated over both species, the entire NPF and the whole season), and the number of weeks during the year that the fishery is open (‘the season’), and the output of the effort allocation model is the number of days targeted at each tiger prawn species by week and tiger prawn stock. The effort allocation model captures the impact of banana prawn abundance on the effort targeted towards tiger prawns, management decision implementation error and how the total fishing effort targeted towards tiger prawns is split by week, stock and tiger prawn species (see Fig. 3 for an overview).

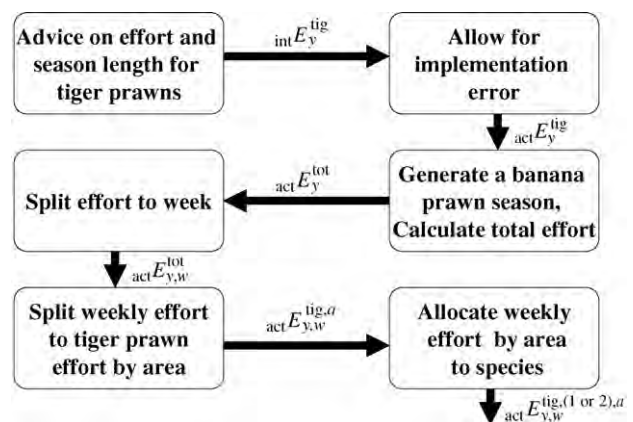


Fig. 3. Flowchart of the algorithm used to determine the number of days of fishing effort targeted at tiger prawns by species, stock, year and week from the total effort directed towards tiger prawns during the year based on the management strategy. The symbols at the arrows are those output from the origin box and is an input to the destination box. These symbols are described in Table 1.

The steps used when calculating the effort for each tiger prawn species by stock area and week are as follows:

1. Calculate the total tiger prawn effort that *actually* occurs during a year by accounting for the impact of implementation error.
2. Select a banana prawn season and calculate the total effort for all prawn species (including banana prawns).
3. Split the total effort into fleet effort by week.
4. Reduce the fleet effort by week by the amount of weekly effort directed towards banana prawns leaving the weekly tiger prawn effort.
5. Split the effort by week into effort by week and stock area.
6. Split the effort by week and stock area into effort by week, stock area and (tiger prawn) target species.

Each of these steps is outlined in more detail below (see Table 1 for the notation used). In several of these steps, a random year from 1990 to 2002 is used to describe the amount of fleet effort during the banana prawn season, the weekly banana and tiger prawn fleet effort patterns and the areas in which the fleet fishes during a given week. The same random year is used for all these cases because the size of the banana prawn catch and the migration pattern of tiger prawns seem to influence the temporal and spatial pattern of the fishery. A different random year is used for each year of the projection period. The size of the banana prawn catch is highly variable between years and is (currently) unpredictable (Fig. 2).

3.1.1. Calculating the total tiger prawn effort that actually occurs

In this operating model, implementation uncertainty is the difference between the number of days actually fished for tiger prawns and the number of days expected to be fished for tiger prawns based on the management strategy. There are several sources of implementation uncertainty: (a) whether a scientific recommendation for a change in effort is accepted by the decision makers, (b) the inability to accurately implement management decisions owing to variability in participation in the

fishery, (c) the difficulty associated with placing restrictions on fishing mortality when multiple species and stocks are being managed and (d) inadequacies in correcting for changes over time in fishing power. The relationship between, $\text{int} E_y^{\text{tig}}$, the management advice on the total effort of the fleet (in days) to be targeted towards tiger prawns (aggregated over both tiger prawn species, the entire NPF and the whole season) during year y and $\text{act} E_y^{\text{tig}}$, the amount of effort actually targeted toward tiger prawns during year y , is modelled using the formula:

$$\text{act} E_y^{\text{tig}} = \text{int} E_y^{\text{tig}} e^{\varepsilon_y}, \quad \varepsilon_y \sim N(0; \sigma^2) \quad (1)$$

where the value for σ is determined by fitting model (1) to the actual effort expended in the NPF and the effort intended to be expended based on the minutes of the Management Advisory Committee for the fishery for the years 1987–2002, ignoring information for the years in which there was no intention to change the amount of effort targeted at tiger prawns.

3.1.2. Accounting for the impact of the fishing on banana prawns

The main impact of the fisheries on the two banana prawn species relates to the number of fishing days available for fishing for tiger prawns (i.e. high recruitment of banana prawns will lead to a shorter tiger season and vice versa). No attempt is made to model the population dynamics of banana prawns given the lack of understanding of the environmental factors that determine the success of banana prawn recruitment, and the likely inability to predict how such environmental factors will change in the future. Instead, an empirical approach is taken to predicting future banana prawn fishing. Specifically, a random year y' is selected at random from the years 1990–2002 (excluding 1994 which was anomalous due to its very early first subseason opening date; this date was stable around 1 April for the remaining years) and the fraction of the total possible effort ‘lost’ to banana fishing is set to that for year y' . These years were selected because the start and end dates of their fishing seasons are considered to be most representative of those likely to occur in future and because the number of boats in the fleet was much higher prior to 1990 than at present.

Table 1
Symbols used in the effort allocation model

$\text{int} E_y^{\text{tig}}$	Fishing effort (in days) during year y directed towards tiger prawns based on the management strategy
$\text{act} E_y^{\text{tig}}$	Fishing effort (in days) during year y actually directed towards tiger prawns (after accounting for implementation error)
$\text{act} E_y^{\text{tot}}$	Fishing effort (in days) during year y directed towards all prawn species (i.e. banana and tiger prawns combined)
$\text{act} E_{y,w}^{\text{tot}}$	Fishing effort (in days) during week w of year y directed towards all prawn species (i.e. banana and tiger prawns combined)
$\text{act} E_{y,w}^{\text{tig}}$	Fishing effort (in days) during week w of year y directed towards tiger prawns
$\text{act} E_{y,w}^{\text{tig},a}$	Fishing effort (in days) directed towards tiger prawns in stock area a during week w of year y
$\text{act} E_{y,w}^{\text{tig},s,a}$	Fishing effort (in days) directed towards tiger prawns of species s in stock area a during week w of year y
$O_{y,w}$	Set equal to 1 if the application of the management strategy allows fishing to occur during week w of year y
y'	Year sampled at random from 1990 to 2002 (excluding 1994)
$\lambda_{y,w}$	Fraction of the effort during week w of year y that was targeted towards banana prawns (Fig. 4)
$\pi_{w,\text{act}}^a$	Average proportion of the effort during week w in stock area a that is targeted at <i>P. semisulcatus</i>
σ	Variation in the relationship between the intended and actual amount of effort directed at tiger prawns

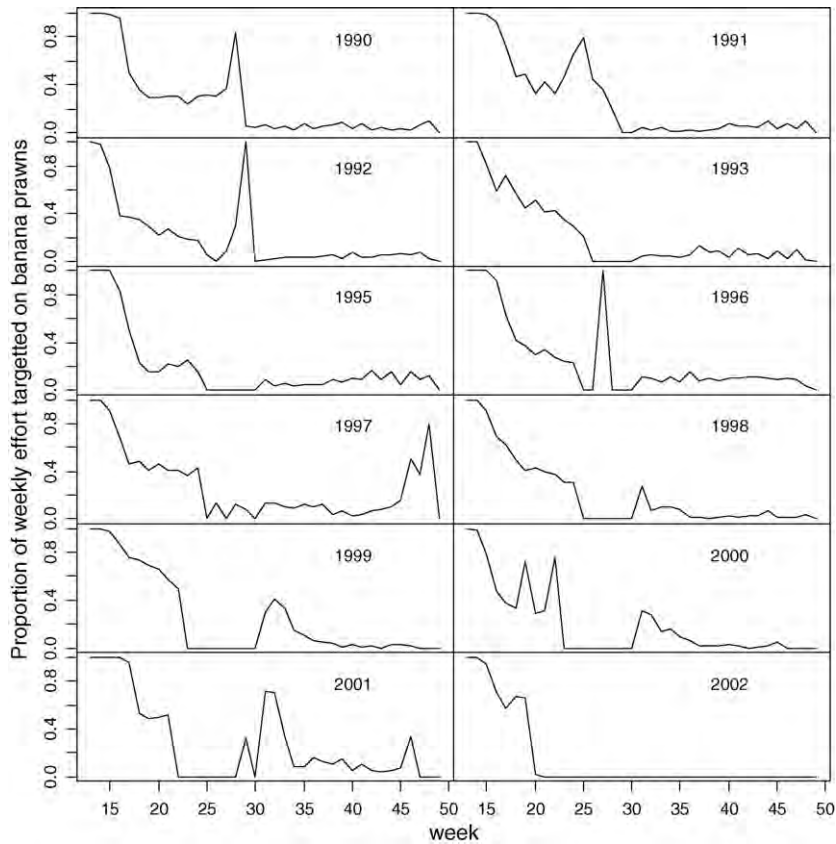


Fig. 4. Proportion of effort by week targeted at the two species of banana prawns.

Given the selection of a year, y' , to determine the nature of the banana prawn fishery during year y , the total effort (directed at all prawn species) during the year y , ${}_{\text{act}}E_y^{\text{tot}}$, is calculated by scaling the actual effort directed towards tiger prawns up by the fraction of the total effort during year y that was directed towards tiger prawns, i.e.:

$${}_{\text{act}}E_y^{\text{tot}} = {}_{\text{act}}E_y^{\text{tig}} \frac{{}_{\text{act}}E_{y'}^{\text{tot}}}{{}_{\text{act}}E_{y'}^{\text{tig}}} \quad (2)$$

3.1.3. Allocating effort to week

The tiger prawn temporal effort pattern is influenced by the subseason start dates, the size of the banana season catch and its persistence over time. Let $O_{y,w}$ be a variable that is 1 if week w of year y is open to fishing and 0 if it is not. The values for $O_{y,w}$ are determined by the management strategy or, as in this paper, pre-specified. The effort directed towards all species is therefore allocated equally to weeks open to fishing according to the formula:

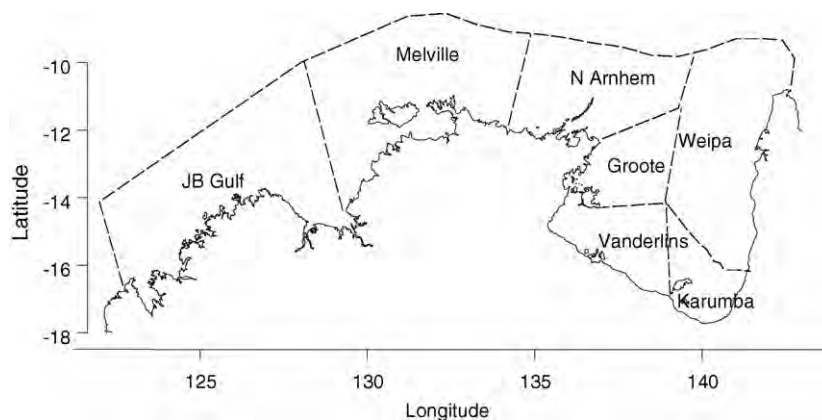


Fig. 5. The stock boundaries identified by Dichmont et al. (2001). The combination of the stock areas Groote, Vanderlins, Karumba and Weipa constitute the Gulf of Carpentaria.

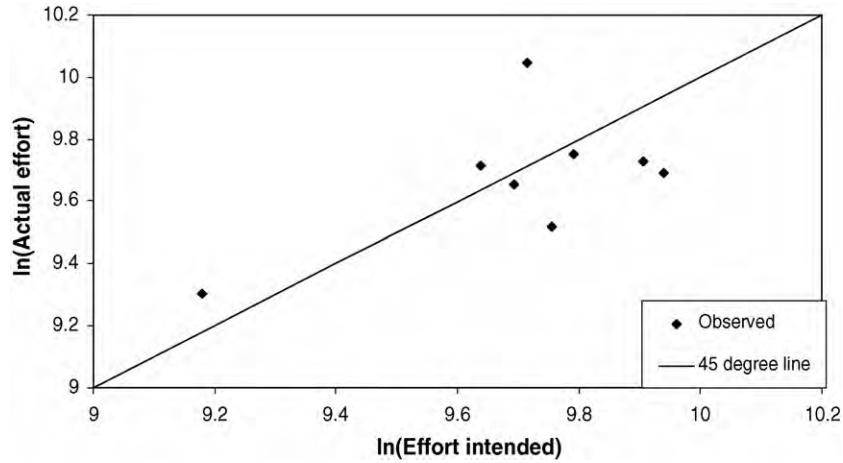


Fig. 6. log–log plot of the effort that was actually to be targeted at tiger prawns vs. the effort that was intended to be targeted at tiger prawns.

$${}_{\text{act}}E_{y,w}^{\text{tot}} = \frac{O_{y,w} \text{ act} E_y^{\text{tot}}}{\sum_{w'} O_{y,w'}} \quad (3)$$

Eq. (3) assumes that all vessels fish throughout the season, but not necessarily all of the effort is directed at tiger prawns. The assumption that all vessels fish throughout the year has not always been true towards the end of a season, but is in general true. The effort directed towards tiger prawns during week w of (future) year y , ${}_{\text{act}}E_{y,w}^{\text{tig}}$ is given by:

$${}_{\text{act}}E_{y,w}^{\text{tig}} = {}_{\text{act}}E_{y,w}^{\text{tot}}(1 - \lambda_{y',w}) \quad (4)$$

where $\lambda_{y',w}$ is the fraction of the actual effort during week w of random year y' that was targeted at either common or red-leg banana prawns (see Fig. 4). The proportion of effort directed at banana prawns is highly variable and may increase at the end of the first season if total effort is very low. Major season and effort changes (including a shorter season) were introduced in 2002, which resulted in a dramatic change in the patterns compared to previous years.

3.1.4. Splitting the effort to stock area

Although models exist for how vessel effort in the NPF is distributed spatially (e.g. Chapman and Beare, 2002), these models

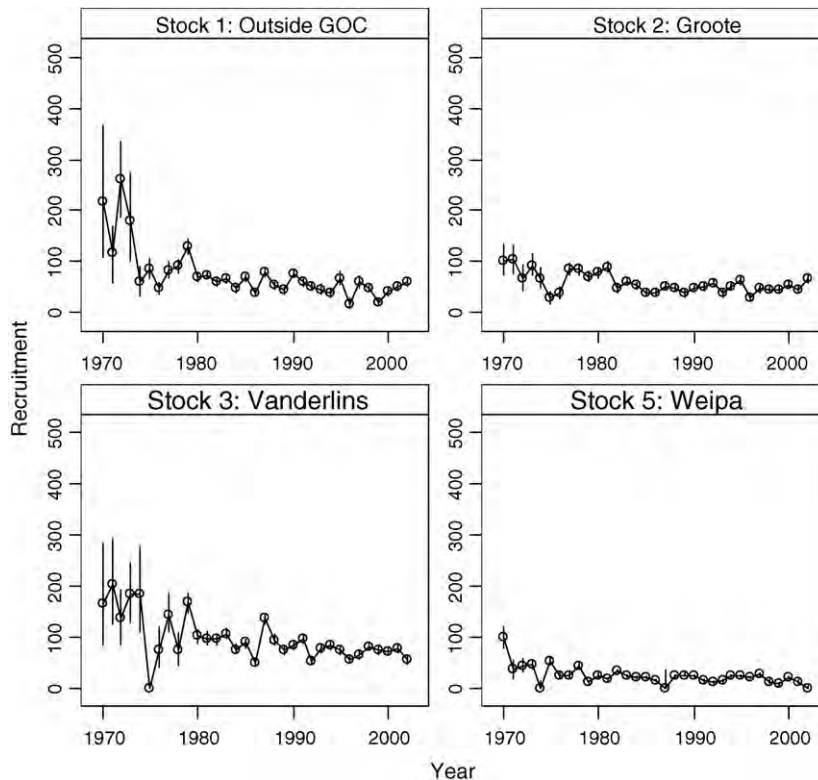


Fig. 7. Recruitment indices (with posterior 5th and 95th percentiles) for *P. semisulcatus* for four stock areas (results for the Karumba area are omitted because of the assumed absence of *P. semisulcatus* from this area).

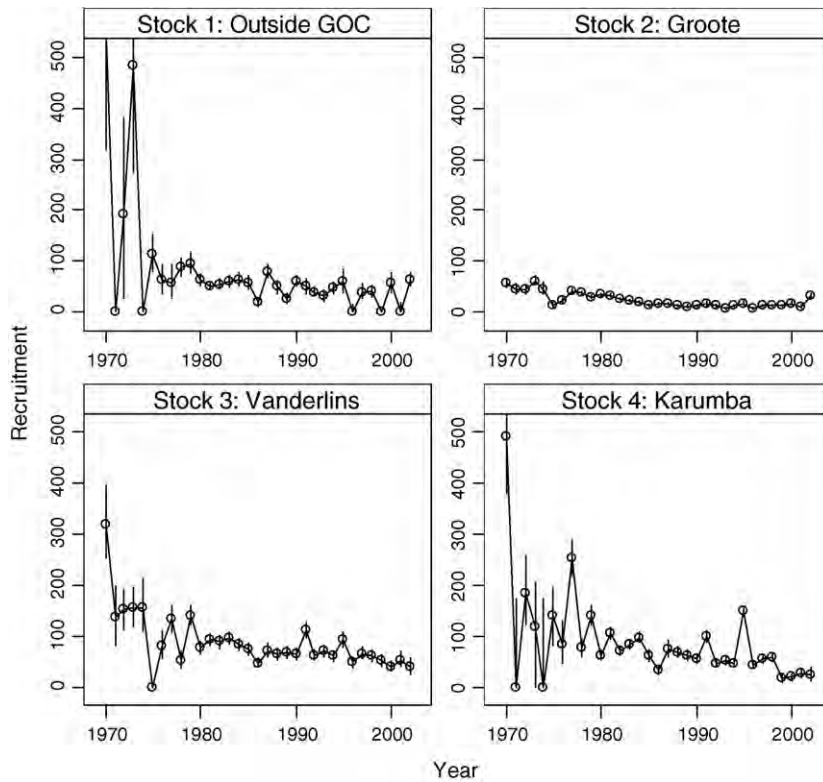


Fig. 8. Recruitment indices (with posterior 5th and 95th percentiles) for *P. esculentus* for four stock areas (results for the Weipa area are omitted because of the assumed absence of *P. esculentus* from this area).

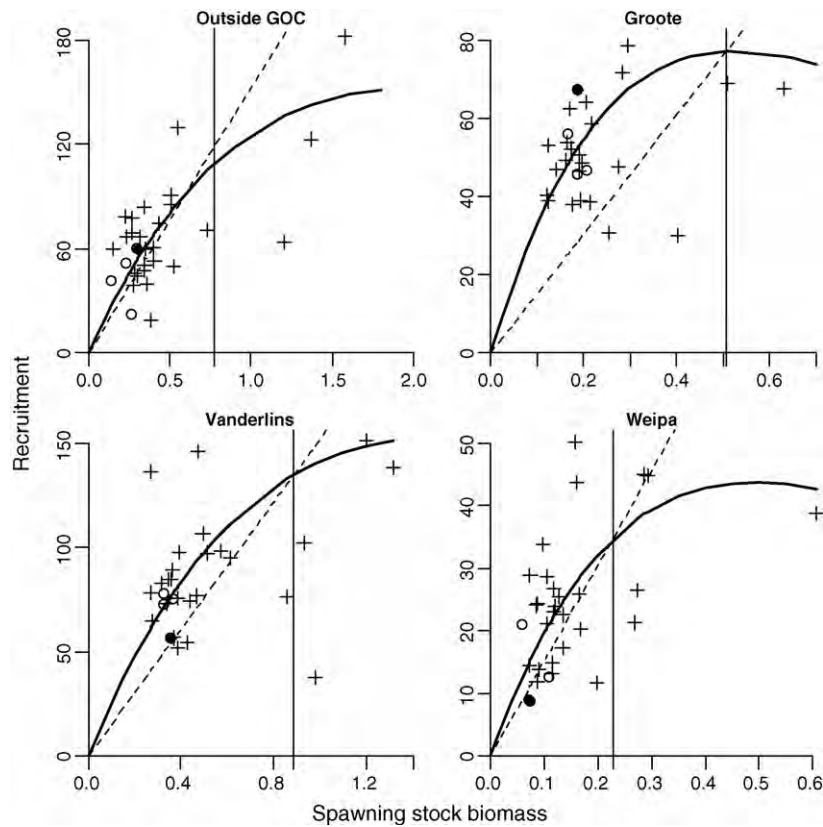


Fig. 9. Ricker stock–recruitment relationships for *P. semisulcatus* for four of the five stock areas. The solid dots are the maximum likelihood estimates of recruitment for the most recent year, the circles are the estimates for the second to fourth most recent years and the crosses are those for other years. The solid lines are the estimated stock–recruitment relationships. The dashed lines are the replacement lines—the amount of recruitment required to replace the original spawning biomass with no fishing mortality.

are not at the same temporal and spatial resolution as the biological component of the operating model. Therefore, rather than using a detailed process model to split the effort by week, to the effort by week and stock area an empirical approach is used instead for this purpose (see Appendix B). The model was fitted to data from 1980 onwards even though y' was selected from 1990 onwards. This is because by 1980 the fishery had reached a certain maturity and its maximum fleet size, with well established spatio-temporal patterns and a good deal of resistance to change in fishing patterns. The largest effect on the tiger prawn spatio-temporal effort pattern is the nature of the banana prawn season that occurs and its persistence through time. It was considered necessary to calibrate the model with as many years of data as possible to include a wide variety of possible banana season events in the analysis.

3.1.5. Splitting the effort to tiger species

The final step of the effort allocation component is to allocate the effort by week and stock area to tiger species (1 is *P. semisulcatus* and 2 is *P. esculentus*). This is achieved using the formula:

$$\text{act} E_{y,w}^{\text{tig},1,a} = \pi_{w,\text{act}}^a E_{y,w}^{\text{tig},a}, \quad \text{act} E_{y,w}^{\text{tig},2,a} = (1 - \pi_{w,\text{act}}^a) E_{y,w}^{\text{tig},a} \tag{5}$$

where $\pi_{w,\text{act}}^a$ is the average proportion of the effort during week w in stock area a that is targeted at *P. semisulcatus*

(see Venables and Dichmont, 2004 for how $\pi_{w,\text{act}}^a$ is estimated).

Eq. (5) has no error associated with it as this has been shown to be small (Dichmont et al., 2001).

3.2. Application to the Northern Prawn Fishery

The operating model for the NPF is based on a five-stock, two-species tiger prawn resource. A total of seven putative tiger prawn stock areas have been identified (Fig. 5). However, the numbers of tiger prawns in two of the three areas outside the Gulf of Carpentaria are very small. Therefore, the areas ‘JB Gulf’, ‘Melville’ and ‘N. Arnhem’ had to be combined into a single stock area denoted ‘Outside GOC’. This leads to a total of five stock areas, four of which are in the Gulf of Carpentaria.

The illustrative example of this paper is based on setting future fishing effort to that for 2002 and the specifications for the fishing season to that for 1999 (chosen because 1999 was the last year before major changes in effort and season length occurred). The operating model uses the base case high fishing power series (Fig. A.1), which is a ‘worst case scenario’ in terms of the current status of the resource (Dichmont et al., 2003a). The projections also ignore any migration among stock areas, which could also be considered to lead to a ‘worst case scenario’ because the impact of excessive effort in one stock area cannot be compensated for to some extent by movement into that stock area from other less exploited stock areas.

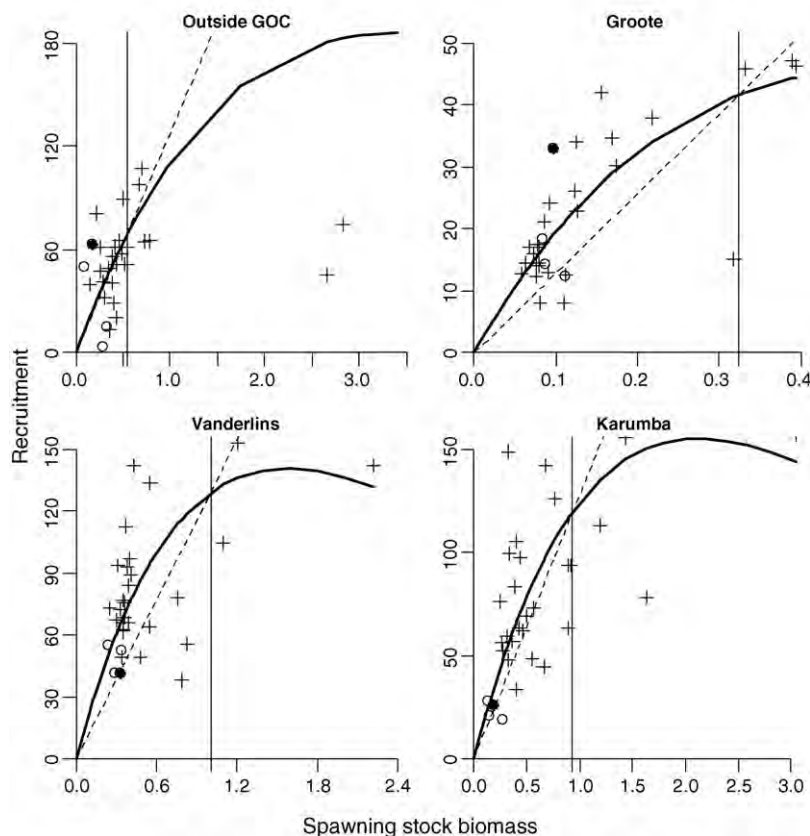


Fig. 10. As for Fig. 9, except that the results pertain to *P. esculentus*.

4. Results and discussion

4.1. Extent of implementation error

Implementation error relates to how well management decisions and policies are applied in practice (Rosenberg and Brault, 1993) and to differences between management advice and the final management decisions in a political and consensus-based decision-making process. This source of uncertainty is often substantially greater than previously believed (Hilborn et al., 2001). Fig. 6 plots the effort that was actually to be targeted at tiger prawns versus the effort that was intended to be targeted at tiger prawns based on the records of the Management Advisory Committee. For cases where the minutes of the Advisory Committee did not state to which species a change in effort applied, the change was assumed to apply to both tiger species. There are several sources for the differences between the intended and actual effort evident in Fig. 6, but broadly speaking they can be divided into two categories: (a) differences between the actual and intended effort and (b) differences between the recommendations from the scientific community regarding effort given agreed decision rules and reference levels and the effort actually selected via the management process. More detailed explanations for the differences in Fig. 6 are:

1. The inability to predict the size of the banana prawn catch in a given year. A large banana prawn catch retains effort on banana prawns thereby indirectly causing a reduction in effort on tiger prawns and vice versa.
2. The inability to predict the behaviour of fishers after an effort reduction aimed at countering increases in fishing power. The fishery is presently managed by controlling headline length using a tradeable gear unit system. When a reduction in effort takes place, each vessel’s headline length is reduced. Given this, fishers can either: (a) trade in gear units to return to their previous headline length (so some vessels have to leave the fishery) or (b) fish with smaller nets. The nett effort reduction depends on the choices the fishery makes. For example, a smaller fleet results in a much larger effort reduction than the same fleet fishing with smaller gear (Venables et al., 2003). In some years, reductions in effort also involved shortening the fishing season. In general, it seems that management underestimated the impact of shortening the season so that the reduction in effort achieved by a change in season exceeded that intended.
3. Errors in determining how fishing efficiency has changed over time. For example, no allowance was made for changes over time in fishing efficiency before the late 1980s; a 5% increase per annum was assumed during the 1990s, after

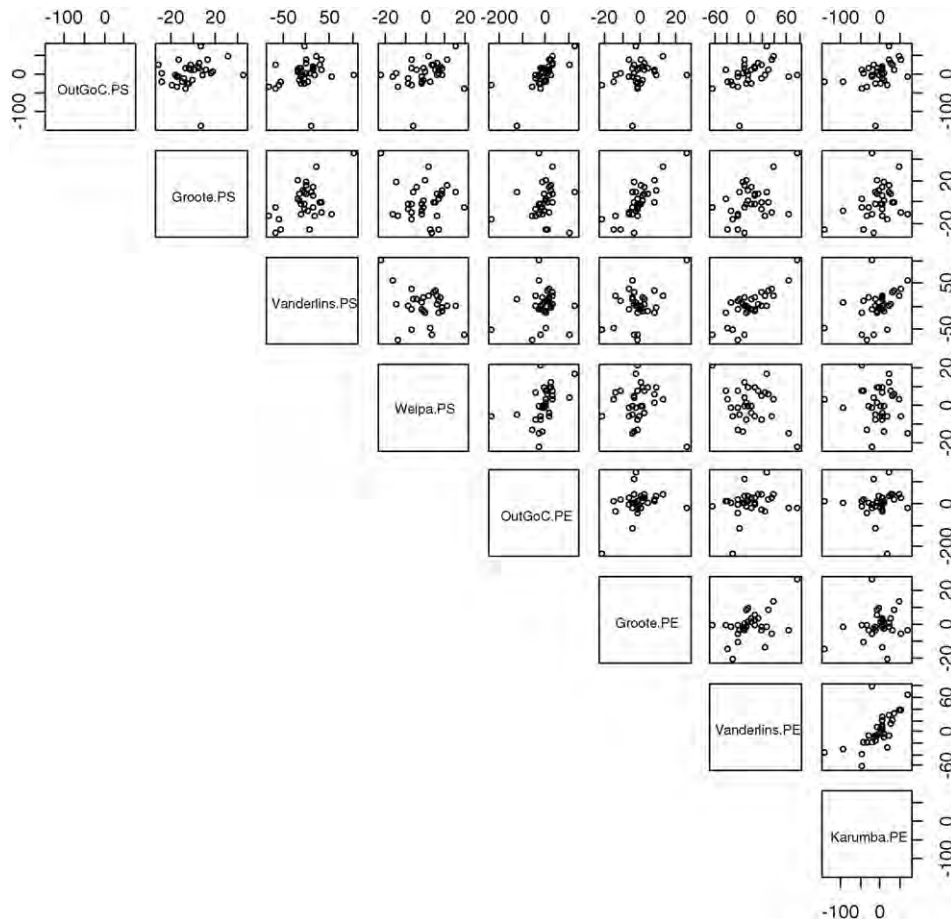


Fig. 11. Interstock and interspecies correlation in the deviations about the estimated stock–recruitment relationship based on the fit of the operating model to the data. ‘PS’ is *P. semisulcatus* and ‘PE’ is *P. esculentus*.

which, yearly changes in fishing efficiency have been modelled. These changes have meant that scientific uncertainty has contributed to implementation error.

4. At times, the scientific management advice suggested a reduction in effort, but this was not accepted by management. Consequently, recommended changes in effort were implemented only about one time out of three.

There is only a very weak relationship between targeted and actual effort and the data would not preclude rejection of the hypothesis that actual effort is independent of intended effort. However, it is reasonable to expect a 1:1 relationship between actual and intended effort. For example, if the intention was to close the fishery, effort would end up being close to zero. The coefficient of variation about the 1:1 line is 0.18, but some of the deviations between the actual and intended effort are as high as 0.3 suggesting that implementation error is quite high. The projections are based on using the 1:1 line because this assumption is effectively the same as the assumption that actual effort is independent of intended effort at the effort levels represented in

Fig. 6, but it behaves more realistically for intended effort levels outside of this range.

One common source of implementation uncertainty involves misreporting of catches, either through black-market landings, misreporting of the species composition of the catch, or high grading and discarding (Butterworth and Punt, 1999). This source of implementation uncertainty is not, however, relevant to this fishery because there is little incentive to hide information about outputs.

Implementation uncertainty has largely been ignored in the evaluation of management strategies. One exception to this is Christensen (1997) who accounted for two sources of implementation uncertainty when evaluating the implications of an effort level or a TAC for the prawn *Pandalus borealis*. These two sources were: (a) the chance that industry pressure would mean that a recommended change in a management measure was not implemented and (b) high grading or discarding. Christensen (1997) concluded that, as expected, if the management measures are modified by a political TAC setting procedure, the fishing mortality may be substantially larger than expected given the

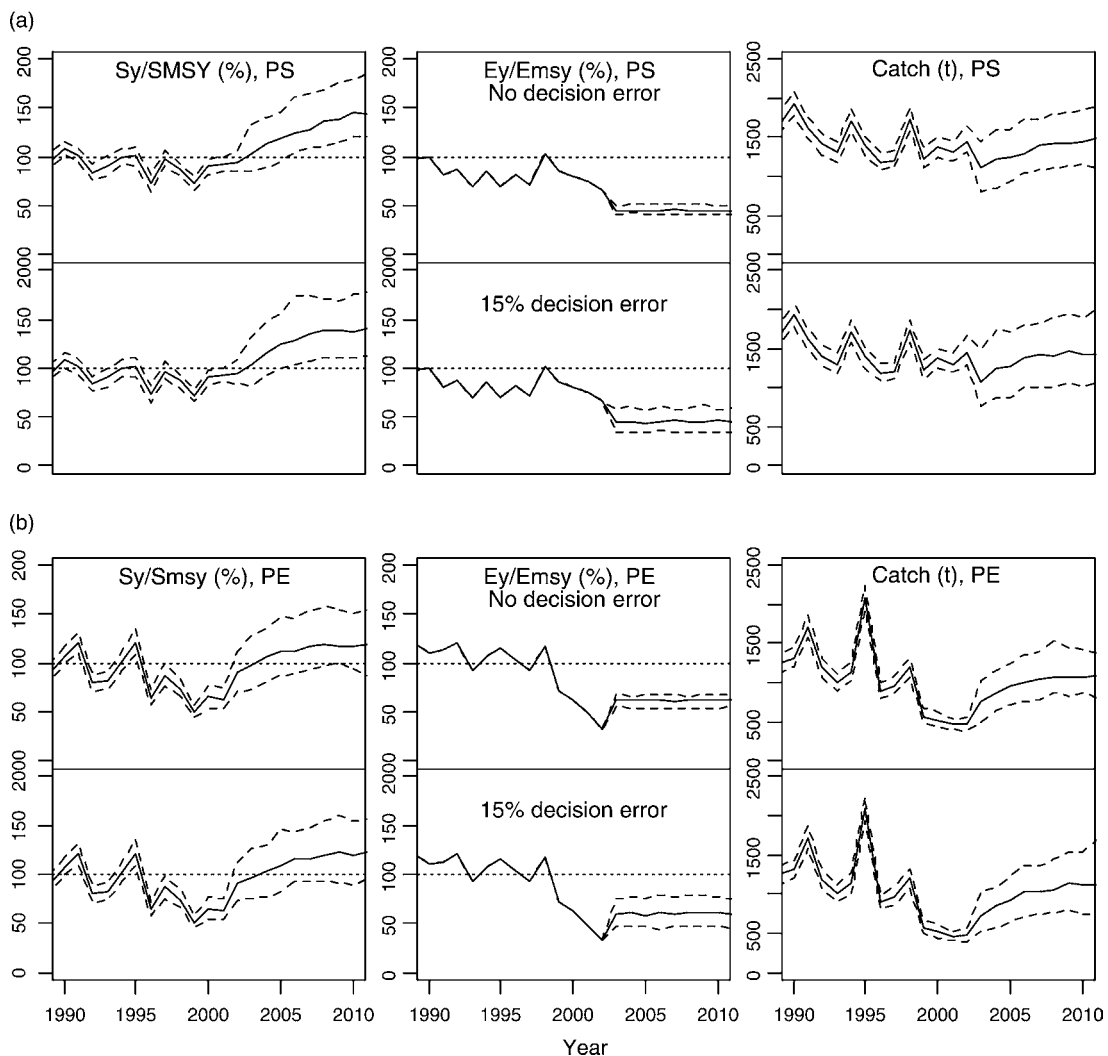


Fig. 12. Time-trajectories of spawning stock size relative to S_{MSY} (%), effort levels relative to E_{MSY} (%) and the total catch (t) for: (a) *P. semisulcatus* (PS) and (b) *P. esculentus* (PE). Results are shown for 1990–2010, with and without implementation (decision) error.

management strategy, which would in turn reduce the average long-term resource rent. Die and Watson (1992) investigated implementation error in the form of non-compliance with spatial closures for the prawn fisheries in the Torres Strait, Australia. They showed that even low levels of implementation error could dissipate most benefits of spatial management for tropical prawn species.

4.2. Estimating the values for the parameters of the operating model

The posterior median time-trajectories of indices of recruitment (with their associated 90% probability intervals) from the operating model are shown in Figs. 7 and 8. The results shown in these and the following figures are based on the base case high fishing power series and the catchability coefficient estimated by Wang (1999). The estimates of recruitment for the years before the mid-1970s are less precise and vary more interannually than those for the years thereafter. There is a slight downward trend in the recruitment for both tiger prawn species after 1980 for all stock areas except Groote.

Some stock areas (e.g. Groote, Vanderlins and Karumba) contain a relatively large biomass of both species, while two areas only contain large numbers of only one species (*P. semisulcatus* in Weipa; *P. esculentus* in Karumba). In areas where numbers of a species are very small, their biomass was assumed to be zero and any catch and effort data are allocated to a nearby stock area (catch of *P. esculentus* in Weipa to Karumba; catch of *P. semisulcatus* in Karumba to Vanderlins). This means that Karumba is assumed to consist exclusively of *P. esculentus* and Weipa of *P. semisulcatus*.

The stock–recruitment relationships differ markedly among species and stock area (Figs. 9 and 10). For example, some of the stock–recruitment relationships exhibit little evidence for compensation at low stock size, which is surprising, but has been a common outcome of assessments for tiger prawns in the NPF (e.g. Wang and Die, 1996; Dichmont et al., 2003a). Furthermore, although a Ricker stock–recruitment relationship has been fitted to the data in Figs. 9 and 10, there is little evidence for a reduction in recruitment at high spawning stock size. As a result, the sensitivity of the results of population projections to the form of the stock–recruitment relationship (Beverton–Holt

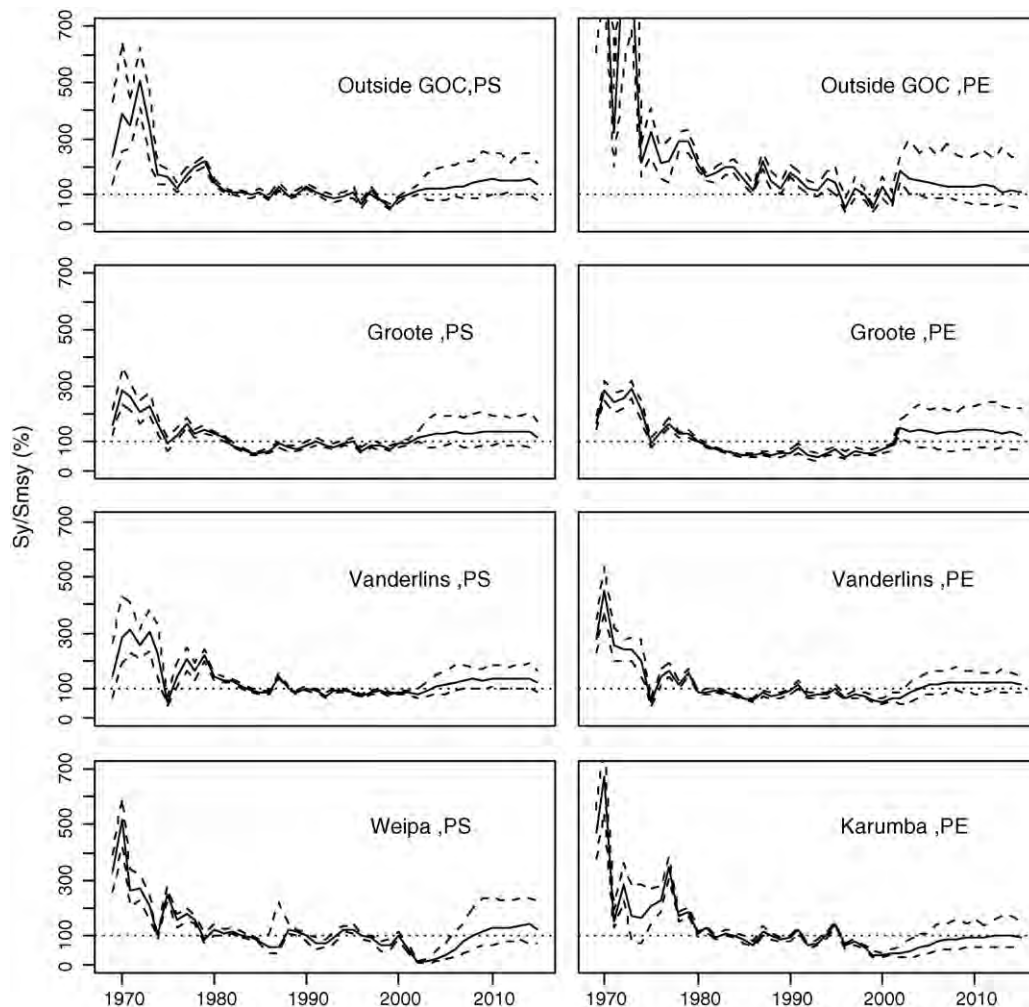


Fig. 13. Spawning stock size relative to S_{MSY} by stock area and species. The results in this figure ignore implementation error.

or Ricker) needs to be included when evaluating the performance of management strategies.

There are some noteworthy correlations between the deviations about the fitted stock–recruitment relationships among stocks and between tiger prawn species (Fig. 11). There are strong positive correlations between tiger prawn species within a stock area (e.g. 0.69, 0.80 and 0.79 for Outside GOC, Groote and Vanderlins, respectively) and within a species between adjacent stock areas (e.g. 0.52 for *P. semisulcatus* in Groote and Vanderlins; 0.65 for *P. esculentus* in Vanderlins and Karumba). There are no strong negative correlations.

4.3. Constant effort projection

The purpose of the example application is to illustrate the behaviour of the operating model and to highlight the complications of a fishery being managed using input controls. The performance of a level of effort is illustrated by plotting the time-trajectories of spawning stock size by species (aggregated over stock area) relative to the spawning stock size that would achieve maximum sustainable yield (S_{MSY}), the annual effort by species relative to that required to achieve the MSY in expectation (E_{MSY}), and the catch by species (e.g. Fig. 12). The intersimulation variation in catches is a consequence of variation in effort directed at each tiger prawn stock, and that about the stock–recruitment relationship. Variation in the effort directed towards each species is due to variation in the algorithm that splits effort spatially and variation in the length of the fishery for banana prawns. For example, a large banana prawn catch delays the switching behaviour from banana to tiger prawns which then also affects which areas are fished (and which tiger prawn species dominates the catch). For example, *P. semisulcatus* tend to migrate beyond the trawl grounds in winter (Crococ and Van der Velde, 1995) and does not occur in Karumba, which is a good banana prawn catch area. As a result, a poor banana prawn season would result in tiger prawns becoming a target during winter which would predominantly consist of *P. esculentus* in the Karumba and neighbouring areas.

Both species were depleted to below S_{MSY} in 2002 with *P. esculentus* stocks being more depleted than *P. semisulcatus* stocks. Since the effort used for projection purposes is much smaller than E_{MSY} , recovery to well above S_{MSY} occurs within a few years (Figs. 12 and 13) and catches increase as catch rates recover. This is the basis of the economic argument that, within limits, a large resource produces higher catch rates which increases profit margins (Rose and Kompas, 2004).

Adding implementation error widens the intervals describing the range of effort expended annually by species (Fig. 12), which then impacts catch and stock status. The median effort trajectory changes only slightly, as would be expected given that the actual effort equals the intended effort in expectation (Fig. 6).

5. Concluding remarks

A model which can act as the operating model for use in applications of the management strategy evaluation approach is developed. This model is fairly general and can capture the

dynamics of multiple stocks of several species. Unlike previous operating models, it can be applied in cases in which management is based on input rather than output controls because it includes a model of effort allocation which, although based primarily on empirical considerations rather than models of individual fisher behaviour, captures the spatial and temporal variation in fishing mortality caused by targeting of other species (in the case of the NPF, banana prawns), and the interannual variation in the spatial distribution of fishing effort. The operating model includes implementation error, which can arise from a variety of sources. In the case of the NPF, implementation error is adequately captured by the assumption that the effort levels actually applied equal those intended, but subject to random (and log-normal) error. However, it would be straightforward to incorporate different models of implementation error such as those considered by Christensen (1997).

The example application of this paper is limited to a simple constant effort projection although, unlike most fisheries projections, account is taken in that projection of multiple species and stocks, and implementation error. Dichmont et al. (2006a,b) use this operating model to evaluate the performance of management strategies for tiger prawns which are candidates for actual use in the NPF, and identify the sources of uncertainty which have the greatest impact on the performance of such management strategies and hence which should be the focus for research.

Acknowledgements

Nick Ellis, Mark Bravington, Yimin Ye, Shijie Zhou and two anonymous reviewers are thanked for their comments on an earlier draft of this paper. The financial support for this research was obtained from the Fisheries Research and Development Corporation and CSIRO. Thanks to the industry, AFMA and Janet Bishop for the data and Janet Bishop for the fishing power series.

Appendix A. Technical details of the operating model

A.1. Basic dynamics

The following equations pertain to each stock area and species. These equations ignore migration among stocks (as this is assumed to be negligible). Therefore, the subscripts for stock area and species are suppressed in the following equations. Table A.1 lists how each of the parameters of the operating model are determined.

The dynamics of the recruited biomass and recruited numbers of each tiger prawn species in each stock area are governed by the equations:

$$B_{y,w+1} = (1 + \rho)B_{y,w} e^{-Z_{y,w}} - \rho e^{-Z_{y,w}} (B_{y,w-1} e^{-Z_{y,w-1}} + w_{k-1} \alpha_{y,w-1} R_{\bar{y}(y,w-1)}) + w_k \alpha_{y,w} R_{\bar{y}(y,w)} \quad (\text{A.1})$$

and

$$\tilde{N}_{y,w+1} = \tilde{N}_{y,w} e^{-Z_{y,w}} + \alpha_{y,w} R_{\bar{y}(y,w)}$$

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

Table A.1
Summary of the base-specific specifications for the parameters of the operating model

Parameter	Base case specification (both species)	
(a) Recruitment and spawning		
Annual recruitment, R_y	Estimated	
Relative weekly recruitment, α_w	Dichmont et al. (2003a)	
Relative weekly spawning, β_w	Dichmont et al. (2003a)	
Stock–recruitment parameters, $\tilde{\alpha}, \tilde{\beta}$	Derived from h and S_0	
Virgin spawning stock index, S_0	Estimated	
Steepness, h	Estimated	
Extent of temporal variation in recruitment, σ_r	Estimated	
Extent of temporal correlation in recruitment, ρ_r	Estimated	
(b) Effort—fishing mortality-related		
Overall catchability by week, \tilde{q}	0.000088 (Wang, 1999) or 2×0.000088	
Relative weekly availability, A_w	Dichmont et al. (2003a)	
By-catch catchability, q_b	11.11 (<i>P. esculentus</i>), 8.26 (<i>P. semisulcatus</i>) (Somers and Wang, 1997)	
Annual efficiency increase, ω_y	Base case high/low	
Target effort, $E_{y,w}^T$	Venables and Dichmont (2004)	
By-catch effort, $E_{y,w}^B$	Venables and Dichmont (2004)	
Catches, $y_{y,w}^{\text{obs}}$	Venables and Dichmont (2004)	
Parameter	Base case specification (<i>Penaeus semisulcatus</i>)	Base case specification (<i>Penaeus esculentus</i>)
(c) Growth		
Brody growth coefficient, ρ	0.979	0.982
Von Bertalanffy growth parameters, ℓ_∞^s, κ^s	Males, 37.5 mm and 0.062 week ⁻¹ ; Females, 51.6 mm and 0.043 week ⁻¹ (Somers and Kirkwood, 1991)	Males, 37.5 mm and 0.034 week ⁻¹ ; Females, 44.8 mm and 0.041 week ⁻¹ (Kirkwood and Somers, 1984)
Length–weight parameters, e^s, f^s	Males, 0.00265 and 2.648; Females, 0.00195 and 2.746	Males, 0.003739 and 2.574; Females, 0.0027 and 2.764
Length-at-recruitment, ℓ_r^s	Males, 26 mm; females, 28 mm	Males, 26 mm; females, 28 mm
Weight-at-recruitment, w_k	Assumed known	Same
Weight the week prior to recruitment, w_{k-1}	$((1 + \rho)w_k - w_{k+1})/\rho$	Same
(d) Other parameters		
Average rate of natural mortality, M	0.045 week ⁻¹ (Wang and Die, 1996)	0.045 week ⁻¹ (Wang and Die, 1996)
Catch in weight residual standard deviation, σ_c	Estimated	Estimated
Fraction of the NPF in each stock area		
Outside GOC	0.396	0.301
Groote	0.140	0.090
Vanderlins	0.319	0.288
Karumba	N/A	0.321
Weipa	0.145	N/A

prawns (of both sexes) at the start of week w of year y and $Z_{y,w}$ is the total mortality during week w of year y :

$$Z_{y,w} = M + F_{y,w} \quad (\text{A.2})$$

α_w is the fraction of the annual recruitment that occurs during week w (assumed to be constant across years), M the instantaneous rate of natural mortality (assumed to be independent of sex, age, species and stock area), $F_{y,w}$ the fishing mortality during week w of year y , $R_{\tilde{y}(y,w)}$ the recruitment during ‘biological year’ $\tilde{y}(y, w)$, w_a the mass of a prawn of age a (k is the age at recruitment), ρ the Brody growth coefficient and $\tilde{y}(y, w)$ is the ‘biological year’ corresponding to week w of year y :

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

Eq. (A.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 data on recruitment indices from surveys (Somers and Wang, 1997).

The fishing mortality during week w of year y on one of the two tiger prawn 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.

$$F_{y,w} = \tilde{q}' A_w q_{y,w} \left(E_{y,w}^T + \frac{E_{y,w}^B}{q_b} \right) \quad (\text{A.4})$$

where $E_{y,w}^T$ is the effort during week w of year y ‘targeted’ towards the species under consideration, $E_{y,w}^B$ the ‘by-catch’ effort during week w of year y (the effort targeted at the other species), $\tilde{q}' = \tilde{q}/P_s$ the catchability coefficient for each stock

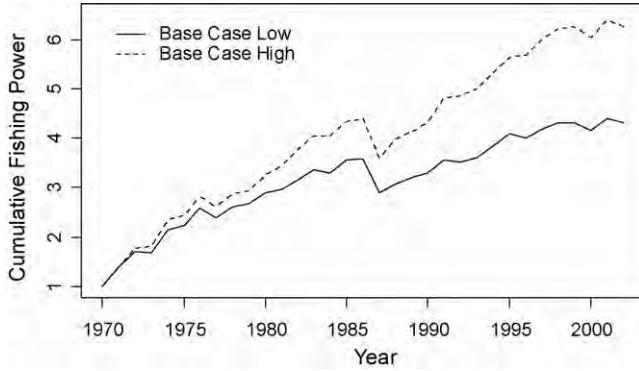


Fig. A.1. The two fishing power scenarios (Dichmont et al., 2003b).

area, \tilde{q} the overall NPF-wide catchability coefficient (i.e. the catchability coefficient for the first week of 1993), P_s the fraction of the total NPF of which the stock area under consideration consists—based on historical logbook data, 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 and $q_{y,w}$ is the relative efficiency during week w of year y :

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

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. (A.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 's in Eq. (A.5) is difficult. 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 (‘base case high’ and ‘base case low’; Dichmont et al., 2003b) are considered (Fig. A.1).

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

$$S_y = \sum_w \beta_w \frac{1 - e^{-Z_{y,w}}}{Z_{y,w}} \tilde{N}_{y,w} \quad (\text{A.6})$$

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

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

$$\hat{R}_{y+1} = \tilde{\alpha} S_y e^{-\tilde{\beta} S_y} \quad (\text{A.7})$$

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 $\tilde{\alpha}$ and $\tilde{\beta}$ are the parameters of the stock–recruitment relationship.

The relationship between the actual recruitment and the conditional mean accounts for serial-correlation:

$$R_y = \hat{R}_y e^{\eta_y}, \quad \eta_{y+1} = \rho_r \eta_y + \sqrt{1 - \rho_r^2} \xi_{y+1},$$

$$\xi_{y+1} \sim N(0; \sigma_r^2) \quad (\text{A.8})$$

where ρ_r is the environmentally driven temporal correlation in recruitment and σ_r is the (environmental) variability in recruitment about the stock–recruitment relationship.

The impact of interstock correlation in the deviations about the stock–recruitment relationship can be examined by estimating the extent of this correlation based on the fit of the operating model to the data.

The recruitment for biological year $y + 1$ depends on the spawning stock size in calendar year y . However, recruitment is deemed to start from 1 October and end at the end of September (the ‘biological’ year) whereas spawning follows a calendar year. This 3-month overlap of spawners and next year’s recruitment is dealt with by:

- generating a recruitment residual for biological year $y + 1$, η_{y+1} (see Eqs. (A.7) and (A.8));
- projecting 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.

Unfortunately, the projection from week 40 until the end of the year depends on the effort by week, stock area and species which, in turn, depends on the recruitment for biological year $y + 1$ through the catches. In principle, this is a system of five stock areas \times two tiger species non-linear equations, and can be solved numerically for R_{y+1} , for each combination of stock area and tiger species, although this is complicated because of the inclusion of random elements in the effort allocation component. Therefore, a simpler formulation has been adopted here. This involves solving for R_{y+1} for each combination of stock area and tiger species by setting the effort splits by stock area and tiger species for year $y + 1$ equal to that for year y and solving for R_{y+1} .

A.2. Likelihood functions

The likelihood function is based on how well the model is able to mimic the historical catch data, i.e. assuming that some function of observed catch-in-weight is normally distributed, and ignoring constants independent of the model parameters:

$$L = \sum_y \sum_w \left\{ \log \sigma_c + \frac{1}{2\sigma_c^2} [k(Y_{y,w}^{\text{obs}}) - k(Y_{y,w})]^2 \right\} \quad (\text{A.9})$$

where σ_c is the residual standard deviation, $Y_{y,w}^{\text{obs}}$ the observed catch (in weight) during week w of year y and $Y_{y,w}$ is the model estimate of the catch (in weight) during week w of year y :

$$Y_{y,w} = \frac{F_{y,w}}{Z_{y,w}} B_{y,w} (1 - e^{-Z_{y,w}}) \quad (\text{A.10})$$

$k()$ is the transformation function (in this case, square root).

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:

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

where Ω represents the temporal correlation among the annual recruitments due to environmental fluctuations. The entries in the matrix Ω are determined from the assumed autocorrelation structure in recruitment (see Eq. (A.8)) 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 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).

A.3. Quantification of uncertainty

Parameter uncertainty is quantified by drawing parameter vectors from a joint Bayesian posterior distribution. Independent uniform prior distributions are assumed for each of the log-recruitments, and hence only vague prior knowledge. This allows the likelihood itself to dominate the posterior distribution. The samples from the posterior distribution are drawn using an MCMC algorithm (Hastings, 1970; Gelman et al., 1995); convergence was evaluated using the program CODA (Smith, 2004).

Appendix B. Splitting the total effort to stock area

Data from the years 1980–2003 were used to construct an empirical model that predicts the proportions of the weekly effort allocated to each stock area as a function of the year, week and, if available, the previous week’s catch rate for each of the five stock areas:

1. The weekly nominal effort for each of the five stock areas was treated as multinomial variate and a multiple logistic model fitted. If \mathbf{x} is the vector of predictor variables for any specific week, then the expected proportions for year y , week w and stock area a , are:

$$p_{y,w}^a = \frac{\exp(\mathbf{x}^T \boldsymbol{\beta}_a)}{\sum_{a=1}^5 \exp(\mathbf{x}^T \boldsymbol{\beta}_a)}, \quad (\text{B.1})$$

where, for identification, we set $\boldsymbol{\beta}_1 = \mathbf{0}$

2. For calibration purposes, only weeks where the total tiger effort exceeded 50 days were used. The predictors used for the model for each area were:
 - a. A separate constant for each combination of year and sub-season (the first sub-season is defined as weeks 1–27 and second as weeks 27–52).

- b. A natural spline in the week of the year with knots at 15, 21, 29, 35, 40 and 45 weeks and boundary knots at 1 and 52 weeks.
 - c. For week w , the log(CPUE) for week $w - 1$ for each of the stock areas, where CPUE was arbitrarily truncated below at 0.5 kg/day and above at 1000 kg/day. These truncations are to reduce the artificial leverage effect of outlying CPUE values.
3. For stability reasons, the parameters of the model were estimated in two stages:
 - a. At the first stage, all weeks where the total tiger effort exceeded 50 days were used, and a model was fitted using the year/season constants and the natural splines for week as predictors.
 - b. At the second stage, only weeks that had a CPUE for the previous week were used. The linear components, $\mathbf{x}^T \boldsymbol{\beta}_a$, from the model fitted in the first stage were used as an offset and only the log(CPUE) values, for each stock area, for the preceding week were used as new predictors.

The prediction of the spatial distribution of the fishing effort for the first week of the season is based on the first stage model only, and for subsequent weeks on the second stage model. This indirect approach provides greater stability to the process than is achievable by trying to include all the data in a single phase. A further refinement of the technique was needed to ensure the stability of the process. The spatial distribution of effort was allocated using a weighted combination of: (a) the historical effort pattern determined from the first stage model and (b) the dynamically varying effort pattern determined from the second stage model. The weights used were either in the proportion 1:1 or 1.5:1. The results from equal weighting are presented in this paper.
 4. The operating model uses a conditional multinomial allocation of effort that can be described as:

$$\{ \text{act} E_{y,w}^{\text{tig},a}, \quad a = 1, \dots, 5 \} | \varepsilon_{y,w}^q \text{ Multinomial} \\ \times \left(\text{act} E_{y,w}^{\text{tig}}; p_{y,w}^a = \frac{\exp(\mathbf{x}_{y,w}^T \boldsymbol{\beta}_a + \varepsilon_{y,w}^a)}{\sum_{a=1}^5 \exp(\mathbf{x}_{y,w}^T \boldsymbol{\beta}_a + \varepsilon_{y,w}^a)} \right) \quad (\text{B.2})$$

where $\varepsilon_{y,w}^a \sim N(0, \sigma^2)$. Experiments suggest that $\sigma^2 = 0.275$ conveys an appropriate amount of overdispersion.

Note that the effort allocation for any particular week in the operating model, other than the initial week of the first and second sub-season, involves the catch and effort data for the previous week. The initial week’s effort allocation is based on the predicted proportions based on the week of the year and the year/season constants from a random year chosen from the calibration set, 1980–2003. The effort allocation component is ‘self-sustaining’ after the initial week’s effort allocation.

References

- Bishop, J., Die, D., Wang, Y.-G., 2000. A generalized estimating equations approach for analysis of the impact of new technology on a trawl fishery. *Aust. N. Z. J. Stat.* 42, 159–177.

- Bishop, J., Venables, W.N., Wang, Y.-G., 2004. Analysing commercial catch and effort data from a Penaeid trawl fishery: a comparison of linear models, mixed models, and generalised estimating equations approaches. *Fish. Res.* 70, 179–193.
- Buckworth, R.C., 1985. Preliminary results of a study of commercial catches, spawning and recruitment of *Penaeus esculentus* and *P. semisulcatus* in the western Gulf of Carpentaria. In: Rothlisberg, P.C., Hill, B.J., Staples, D.J. (Eds.), *Proceedings of the Second Australian National Prawn Seminar (NPS2)*. Cleveland, Australia, pp. 213–225.
- Butterworth, D.S., Cochrane, K.L., De Oliveira, J.A.A., 1997. Management procedures: a better way to manage fisheries? The South African experience. In: Pickett, E.K., Huppert, D.D., Sissenwine, M.P. (Eds.), *Global Trends: Fisheries Management*. Am. Fish. Soc. Symp. 20, 83–90.
- Butterworth, D.S., Punt, A.E., 1999. Experiences in the evaluation and implementation of management procedures. *ICES J. Mar. Sci.* 56, 985–998.
- Cartwright, I., 2005. The Australian Northern Prawn Fishery. In: Cunningham, S., Bostock, T. (Eds.), *Successful Fisheries Management Issues, Case Studies and Perspectives*. SIFAR/World Bank Study of Good Management Practice in Sustainable Fisheries. Eburon Academic Publishers, The Netherlands, pp. 197–231.
- Chapman, L., Beare, S., 2002. Economic impact of the Northern Prawn Fishery Amendment Plan. In: ABARE Report Prepared for The Fisheries and Aquaculture Branch. Agriculture, Fisheries and Forestry, Canberra, Australia, 35 pp.
- Christensen, S., 1997. Evaluation of management strategies—a bioeconomic approach applied to the Greenland Shrimp Fishery. *ICES J. Mar. Sci.* 54, 412–426.
- Coles, R.G., Poiner, I.R., Kirkman, H., 1989. Regional studies—seagrasses of north-eastern Australia. In: Larkum, A.W.D., McComb, A.J., Shepherd, S.A. (Eds.), *Biology of Seagrasses: Aquatic Plant Studies*, vol. 2. Elsevier, Amsterdam, pp. 261–278 (Chapter 9).
- Condie, S.A., Loneragan, N.R., Die, D.J., 1999. Modelling the recruitment of tiger prawns *Penaeus esculentus* and *P. semisulcatus* to nursery grounds in the Gulf of Carpentaria, Northern Australia: implications for assessing stock–recruitment relationships. *Mar. Ecol. Prog. Ser.* 178, 55–68.
- Crocos, P.J., Van der Velde, T.D., 1995. Seasonal, spatial and interannual variability in the reproductive dynamics of the grooved tiger prawn *Penaeus semisulcatus* in Albatross Bay, Gulf of Carpentaria, Australia: the concept of effective spawning. *Mar. Biol.* 122, 557–570.
- De la Mare, W.K., 1996. Some recent developments in the management of marine living resources. In: Floyd, R.B., Shepherd, A.W., De Barro, P.J. (Eds.), *Frontiers of Population Ecology*. CSIRO Publishing, Melbourne, Australia, pp. 599–616.
- Dichmont, C.M., Die, D., Punt, A.E., Venables, W., Bishop, J., Deng, A., Dell, Q., 2001. Risk analysis and sustainability indicators for the prawn stocks in the Northern Prawn Fishery. Report of FRDC 98/109. CSIRO Marine Research, Cleveland, 187 pp.
- Dichmont, C.M., Punt, A.E., Deng, A., Dell, Q., Venables, W., 2003a. Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery. *Fish. Res.* 65, 335–350.
- Dichmont, C.M., Bishop, J., Venables, W.N., Sterling, D., Penrose, J., Rawlinson, N., Eayrs, S., 2003b. A new approach to fishing power analyses and its application in the Northern Prawn Fishery. Report of AFMA Research Fund R99/1494. CSIRO Marine Research, Cleveland, 700 pp.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006a. Management strategies for short lived species: the case of Australia's Northern Prawn Fishery. 2. Choosing appropriate management strategies using input controls. *Fish. Res.* 82, 221–234.
- Dichmont, C.M., Deng, A., Punt, A.E., Venables, W.V., Haddon, M., 2006b. Management strategies for short lived species: the case of Australia's Northern Prawn Fishery. 3. Factors affecting management and estimation performance. *Fish. Res.* 82, 235–245.
- Die, D., Ellis, N., 1999. Aggregation dynamics in penaeid fisheries: banana prawns (*Penaeus merguensis*) in the Australian Northern Prawn Fishery. *Aust. J. Mar. Freshwater Res.* 50, 667–675.
- Die, D., Loneragan, N., Haywood, M., Vance, D., Manson, F., Taylor, B., Bishop, J., 2001. Indices of recruitment and effective spawning for tiger prawn stocks in the Northern Prawn Fishery. Report of FRDC 95/014. CSIRO Marine Research, Cleveland, 180 pp.
- Die, D.J., Watson, R.A., 1992. A per-recruit simulation model for evaluating spatial closures in an Australian penaeid fishery. *Aquat. Liv. Res.* 5, 145–153.
- FAO, 1996. Precautionary approach to capture fisheries. Part 2. Scientific papers. FAO Fish. Tech. Paper No. 350, Part 2. FAO, Rome, 210 pp.
- Gelman, A., Carlin, J.B., Stern, H.S., Rubin, D.B., 1995. *Bayesian Data Analysis*. Chapman and Hall, London.
- Hastings, W.K., 1970. Monte Carlo sampling methods using Markov chains and their applications. *Biometrika* 57, 97–109.
- Hilborn, R., Maguire, J.-J., Parma, A.M., Rosenberg, A.A., 2001. The precautionary approach and risk management: can they increase the probability of successes in fishery management? *Can. J. Fish. Aquat. Sci.* 58, 99–107.
- Hill, B.J., Wassenberg, T.J., 1985. A laboratory study of the effect of streamer tags on mortality, growth, moulting and duration of nocturnal emergence of the tiger prawn *Penaeus esculentus* (Haswell). *Fish. Res.* 3, 223–235.
- Kirkwood, G.P., Smith, A.D.M., 1996. Assessing the precautionary nature of fishery management strategies. FAO Fish. Tech. Paper No. 350, Part 2, pp. 141–158. FAO, Rome, 210 pp.
- Kirkwood, G.P., Somers, I.F., 1984. Growth of two species of tiger prawn, *Penaeus esculentus* and *P. semisulcatus*, in the western Gulf of Carpentaria. *Aust. J. Mar. Freshwater Res.* 35, 703–712.
- Poiner, I.R., Staples, D.J., Kenyon, R., 1987. Seagrass communities of the Gulf of Carpentaria, Australia. *Aust. J. Mar. Freshwater Res.* 38, 121–131.
- Pownall, P.C. (Ed.), 1994. *Australia's Northern Prawn Fishery: The First 25 Years*. NPF25, Cleveland, Australia, 179 pp.
- Punt, A.E., 1992. Selecting management methodologies for marine resources, with an illustration for southern African hake. *S. Afr. J. Mar. Sci.* 12, 943–958.
- Punt, A.E., Smith, A.D.M., 1999. Harvest strategy evaluation for the eastern stock of gemfish (*Rexea solandri*). *ICES J. Mar. Sci.* 56, 860–875.
- Punt, A.E., Smith, A.D.M., Cui, G., 2002. Evaluation of management tools for Australia's South East Fishery. 1. Modelling the South East Fishery taking account of technical interactions. *Mar. Freshwater Res.* 53, 615–629.
- Robins, C.M., Wang, Y.-G., Die, D., 1998. The impact of global positioning systems and plotters on fishing power in the Northern Prawn Fishery, Australia. *Can. J. Fish. Aquat. Sci.* 55, 1645–1651.
- Rose, R., Kompas, T., 2004. Management options for the Australian Northern Prawn Fishery: an economic assessment. ABARE eReport 04.12. Report for Fisheries Resources Research Fund. Canberra, 47 pp.
- Rosenberg, A.A., Brault, S., 1993. Choosing a management strategy for stock rebuilding when control is uncertain. In: Smith, S.J., Hunt, J.J., Rivard, D. (Eds.), *Risk Evaluation and Biological Reference Points for Fisheries Management*. Can. Spec. Publ. Fish. Aquat. Sci., 120: viii +442 p., 243–249, NRC.
- Sainsbury, K.J., Punt, A.E., Smith, A.D.M., 2000. Design of operational management strategies for achieving fishery ecosystem objectives. *ICES J. Mar. Sci.* 57, 731–741.
- Smith, B.J., 2004. Bayesian Output Analysis Program (BOA), Version 1.1 User's Manual. R Library, 43 pp. (<http://www.public-health.uiowa.edu/boa/boa.pdf>).
- Smith, A.D.M., Sainsbury, K.J., Stevens, R.A., 1999. Implementing effective fisheries-management systems—management strategy evaluation and the Australian partnership approach. *ICES J. Mar. Sci.* 56, 967–979.
- Somers, I.F., 1990. Manipulation of fishing effort in Australia's penaeid prawn fisheries. *Aust. J. Mar. Freshwater Res.* 41, 1–12.
- Somers, I., Wang, Y., 1997. A simulation model for evaluating seasonal closures in Australia's multispecies Northern Prawn Fishery. *N. Am. J. Fish. Manage.* 17, 114–130.
- Somers, I.F., Crocos, P.J., Hill, B.J., 1987. Distribution and abundance of the tiger prawns *Penaeus esculentus* and *P. semisulcatus* in the north-western Gulf of Carpentaria, Australia. *Aust. J. Mar. Freshwater Res.* 38, 63–78.
- Somers, I.F., Kirkwood, G.P., 1991. Population ecology of the grooved tiger prawn, *Penaeus semisulcatus*, in the north-western Gulf of Carpentaria,

- Australia: growth, movement, age structure and infestation by the bopyrid parasite *Epipenaeon ingens*. Aust. J. Mar. Freshwater Res. 42, 349–367.
- Vance, D.J., Staples, D.J., Kerr, J.D., 1985. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguensis*) in the Gulf of Carpentaria, Australia. J. Cons. Ciem. 42, 83–97.
- Venables, W.N., Dichmont, C.M., 2004. A generalized linear model for catch allocation: an example from Australia's Northern Prawn Fishery. Fish. Res. 70, 405–422.
- Venables, W.N., Dichmont, C.M., Toscas, P., Bishop, J., Ye, Y., Deng, R., 2003. Report to NORMAC on effort trade-off proposals for the NPF. AFMA Research Fund project 2003, 53 pp.
- Wang, Y.-G., 1999. A maximum-likelihood method for estimating natural mortality and catchability coefficient from catch-and-effort data. Mar. Freshwater Res. 50, 307–311.
- Wang, Y.-G., Die, D., 1996. Stock–recruitment relationships of the tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) in the Australian Northern Prawn Fishery. Mar. Freshwater Res. 47, 87–95.