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Risk versus economic performance in a mixed fishery: the case of the Northern Prawn Fishery in Australia

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Abstract

Balancing bio-economic risks and high profit expectations is often a major concern in fisheries management. We examine this trade-off in the context of the Australian Northern Prawn Fishery (NPF), which is managed to achieve Maximum Economic Yield (MEY). The fishery derives its revenue from different prawn species with more or less uncertain dynamics and recruitment. A multi-species bio-economic and stochastic model is used to examine the trade-offs between mean economic performance of the fishery and the variance of this performance, under a range of economic scenarios and strategies with respect to fleet capacity and effort allocation. Simulation results show that the observed fishing strategy displayed by the fleet might be interpreted as seeking the best compromise between performance and risk. Increases in fleet size or in the annual fishing effort of vessels would only improve the expected economic performance of the fishery at the cost of increased variability of this performance. Under a likely economic scenario, adaptation of the fishery to maintain current levels of economic performance is likely to depend on the extent to which operators in the fishery are willing to accept higher levels of economic risk.

Keywords: Bio-economic modelling, uncertainty, risk-performance trade-offs, scenarios, fishing strategy, Northern Prawn Fishery.

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1. Introduction

Globally, many capture fisheries do not achieve their full economic potential and are subject to excess capacity (Munro, 2010). For some fisheries, this may be due to failure in regulating the race to fish. Other fisheries may be managed to achieve Maximum Sustainable Yield (MSY), rather than Maximum Economic Yield (MEY). In some cases, social considerations may have dominated the management decision process leading to the approval of even higher levels of capacity. In other cases, differences between observed harvesting levels of individual species and the levels (e.g. Total Allowable Catches (TAC)) which would ensure MEY may be related to the fact that commercial fishers operate across a range of species, with varying ability to target these species separately, leading to difficulties in identifying optimal fishery-wide levels of fishing capacity and allocation of fishing effort. Moreover, revenues from fisheries may vary greatly from year to year owing to natural variation in fish stocks (Kasperski and Holland, 2013) that cannot be predicted with any reliability, leading to varying levels of economic risks for fishing operators (Sethi, 2010). In multi-species fisheries, the different fish stocks contributing to the overall catch may present different levels of natural variability, such that the choice of fishing strategies can be associated with trade-offs between mean and variance of the fishery's economic yield. While maximising economic yield is usually seen as a desirable objective for fisheries management, industry stakeholders usually also value stability over time. This may be due to risk aversion, but also to the need to maintain markets, avoid market saturation and guide investment decisions relating to non-malleable capital (Holland and Herrera, 2009).

This article focuses on the analysis of trade-offs between mean performance and performance variability of economic yield in a fishery, managed with the objective of achieving MEY, but in which the set of target species have different levels of environmentally-driven variability of recruitment. The analysis is based on a bio-economic modelling approach, and is applied to the case of the Northern Prawn Fishery (NPF) in Australia.

The NPF, which is located off Australia's northern coast (figure 1), is a multi-species trawl fishery based on several tropical prawn species.

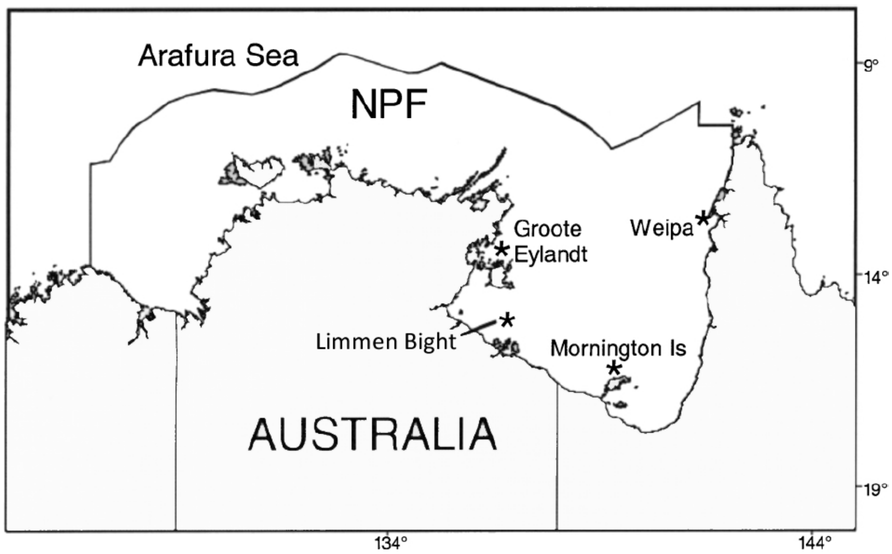


Figure 1: Map of northern Australia showing the extent of the Northern Prawn Fishery (Milton, 2001).

The NPF has a long history of collaborative management involving scientists, industry, and the fishery managers (Australian Fisheries Management Authority (AFMA)). It is one of Australia's most valuable federally managed commercial fisheries, and has regularly returned a positive profit (Rose and Kompas, 2004) since its establishment in the late 1960s. However, in recent years the fishery has experienced a decline in value as a result of the increased supply of aquaculture-farmed prawns to both domestic and international markets, strong Australian currency and increasing fuel prices (Punt et al., 2011). Of the fifty species of prawns that inhabit Australia's tropical northern coastline, the trawl fishery targets only nine commercial species of prawns including tiger, banana and endeavour prawns. Revenue in the fishery is mostly obtained from the harvest of white banana prawns (*Penaeus merguiensis*), grooved tiger prawns (*Penaeus semisulcatus*) and brown tiger prawns (*Penaeus esculentus*), these three species accounting for 95% of the total annual landed catch value of the fishery (ABARE-BRS, 2010).

The NPF operates over two 'seasons' spanning the period April to November with a mid-season closure of variable length from June to August. Seasonal closures are in place to protect small prawns (closure from December to March), as well as spawning individuals (mid-season closure) (AFMA and CSIRO, 2012). The fishery effectively consists of two sub-fisheries that are (to a large degree) spatially and temporally separate. The 'banana prawn sub-fishery' is effectively a single species fishery based on the white banana prawn, while the 'tiger prawn sub-fishery' is a mixed species fishery targeting grooved and brown tiger prawns, as well as blue endeavour prawns (*Metapenaeus endeavouri*) which are caught as by product[1] (Woodhams et al., 2011).

The banana prawn sub-fishery operates mostly during the first season, which generally lasts between four and eight weeks depending on recruitment, while the tiger prawn sub-fishery occurs mostly during the second season (although in poor banana prawn years may start earlier). White banana prawns form dense aggregations ('boils') which are easily identified from spotter planes. White banana prawn stocks are strongly influenced by weather patterns, and the highest seasonal catches generally follow higher than average rainfall during the preceding summer (Vance et al., 1985). The variability of white banana prawn stocks makes it difficult to set catch or effort limits in a way that protects spawning stocks but also allows operators to profit from years in which prawns are abundant

[1] A third sub-fishery exists in the Joseph Bonaparte Gulf in the far western part of the fishery based on red-leg banana prawns (*Fenneropenaeus indicus*). This sub-fishery is exploited by a relatively small number of vessels as it occurs at the same time as the (more valuable) tiger prawn sub-fishery, and is not included in the subsequent analysis.

(Buckworth et al., 2013). The effort during the first season depends very little on tiger or endeavour prawn abundances.

In the second season, the fleet switches to the tiger prawn sub-fishery, for which catches per unit effort are lower but less variable. However, if banana prawns are still available in large enough numbers (catch rate for banana prawns above 500kg/boat per day), some vessels will continue to target them[2]. Key aspects of the biology, habitat requirements, catchability and value differ between the major target species of the tiger and banana prawn sub-fisheries in ways that have an important bearing on management. Tiger and blue endeavour prawn stocks are more stable and predictable than the white banana prawn stock. Moreover the former species are generally more dispersed relative to white banana prawns. Consequently, even though the same vessels are used in both sub-fisheries, the fishing gears and techniques differ. While banana prawns are caught in daytime trawls of relatively short duration (but lot of time searching), tiger prawns are taken at night (daytime trawling is banned during the tiger prawn season to reduce the capture of spawning tiger prawns (AFMA and CSIRO, 2012). The two tiger prawn species exhibit some spatial and temporal separation, with brown tiger prawns being dominant in the first part of the tiger season and grooved tiger prawns being dominant in the second part. However, by-catch of the other tiger prawn species as well as endeavour species is prevalent over the whole season, providing an example of a classic mixed fishery in which it is impossible to target one species perfectly (Pascoe et al., 2010).

The NPF is currently managed using input controls in the form of limited entry, gear restrictions, as well as time and spatial closures. Management of the fishery has been supported by the development and application of a full Management Strategy Evaluation (MSE) approach (Dichmont et al., 2006, 2008, Venables et al., 2009). Following several industry and government funded buy-back schemes, the NPF now comprises 52 vessels, which is believed to be the number required to achieve Maximum Economic Yield (MEY) in the fishery (Barwick, 2011). By comparison, more than 120 vessels operated in the fishery a decade ago, and over 300 vessels in the 1970s and 1980s.

To date, bio-economic analysis of the fishery has been largely focused on the more predictable component of the fishery, namely the tiger prawn sub-fishery (Dichmont et al., 2008, 2010, Punt et al., 2011). The analysis presented here uses a simplified representation of the bio-economic dynamics of the fishery, integrating the more variable banana prawn resource. Thanks to the bio-economic

[2]This happens relatively infrequently and in most years white banana prawn catches are less than two percent of the total catch in the tiger prawn sub-fishery.

model accounting for both sub-fisheries, trade-offs between mean performance and risk associated are assessed within a selection of possible management strategies for the NPF, taking into account the distribution of fishing effort across sub-fisheries. Mean-variance analyses are examined under current management, and performances are then compared under a range of fishing strategies, including analysis of sensitivity to different assumptions regarding changes in fuel and prawn prices.

2. Material and Methods

The bio-economic model developed here synthesizes previous modelling work by Dichmont et al. (2003, 2008) and Punt et al. (2010, 2011) on the NPF, and extends it by explicitly modelling both tiger and banana prawn sub-fisheries. The model is based on recent developments in mixed fisheries bio-economic modelling (Gourguet et al., 2013). It includes white banana prawns, grooved tiger, brown tiger prawns and blue endeavour prawns. All of them are short lived species; however, while white banana prawns are with highly variable recruitments, tiger and endeavour prawns are associated to less variable recruitments. Our analysis captures the major components and interactions that characterise the NPF (figure 2), as described in section 1.

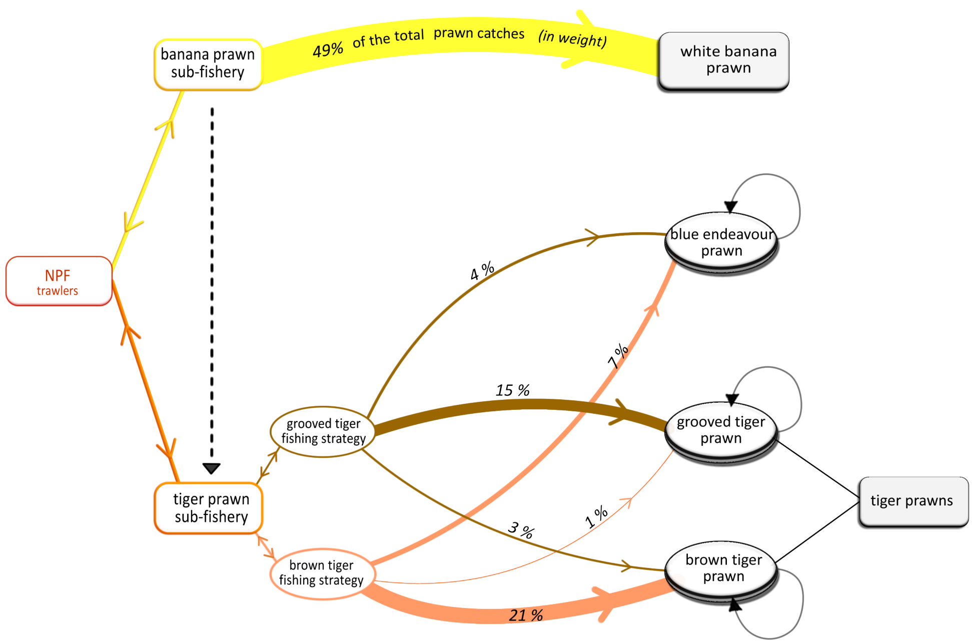


Figure 2: Stylized representation of the Northern Prawn Fishery used as a basis to develop the bio-economic model. The width of the arrows between the sub-fisheries and various prawns are proportional to the proportion of the catch by species and by sub-fishery (tiger - with differentiation of grooved and brown tiger prawn fishing strategies - and banana prawn sub-fisheries) compared to the total catch of the fishery in 2010. The dashed arrow between tiger and banana prawn sub-fisheries illustrates the influence of the banana prawn season on the tiger prawn fishing effort.

2.1. A multi-species, stochastic and dynamic model

Population dynamics of tiger and blue endeavour prawns are based on a multi-species weekly time-step, sex-structured population model with Ricker stock-recruitment relationship and environmental uncertainties. The population dynamics model allows for week-specificity in recruitment, spawning, availability and fishing mortalities. Dynamics of grooved and brown tiger prawns are based on size-structured models, whereas the dynamics of blue endeavour is based on an aggregated population model. White banana prawns are represented without explicit density-dependence mechanisms, due to highly variable recruitment and absence of a defined stock-recruitment relationship.

2.1.1. Tiger prawns: sex- and size-structured population dynamic models

Catches of grooved and brown tiger prawns are recorded and marketed together as 'tiger prawns'. However, since each species has a unique life cycle and occupies a different ecological niche, it is important that the population dynamics model be species-specific. The population dynamics of grooved and brown tiger prawns (s = 1 and 2, respectively) are based on a sex- and size-structured model relying on a weekly time-step as presented in Punt et al. (2010) and given by the equation (1):

$$\vec{\mathrm{N}}_s(t+1) = \mathrm{f}\Big(t, \vec{\mathrm{N}}_s(t), \vec{F}_s(t)\Big), \qquad s = 1, 2. \tag{1}$$

where $\vec{\mathrm{N}}_s(t)$ is the vector of abundance $\mathrm{N}_{s,x,l}(t)$ of prawns of species s of sex x (with x = ♂ for male and ♀ for female) in size-class l (1-mm size-classes between lengths of 15 to 55 mm) alive at the start of time t which corresponds to one time step (i.e. one week), and $\vec{F}_s(t)$ is the vector of fishing mortality $F_{s,l}(t)$ of animals of species s and size-class l at time t. Details on fishing mortality are given in AppendixA.3. The dynamic function f accounts for the species recruitment and mortality mechanisms as detailed in AppendixA.1.

Spawning stock size index $\mathrm{S}_s(y(t))$ of the species s for the year $y(t)$ is given by:

$$\mathrm{S}_s(y(t)) = \frac{1}{52} \sum_{t=52\left(y(t)-1\right)+1}^{52y(t)} \beta_s(t) \sum_l \gamma_{s,l} \frac{1-\exp\left(-Z_{s,l}(t)\right)}{Z_{s,l}(t)} \mathrm{N}_{s,♀,l}(t), \qquad s = 1, 2. \tag{2}$$

where $y(t)$ is the year corresponding to the time t. $\beta_s(t)$ measures the relative amount of spawning of species s during time t, and $\gamma_{s,l}$ corresponds to the proportion of females of species s in size-class l that are mature. $Z_{s,l}(t)$ stands for the total mortality of animals of species s in size-class l at time t and is defined by:

$$Z_{s,l}(t) = M_s + F_{s,l}(t). \tag{3}$$

with M_s the natural mortality of animal of species s.

2.1.2. *Blue endeavour prawn: an aggregated population dynamic model*

The population dynamics of blue endeavour prawn (species $s = 3$) is modelled as an aggregated process governed by equation (4):

$$\mathrm{N}_{3,x}(t+1) = \mathrm{N}_{3,x}(t) \exp\left(-Z_3(t)\right) + \alpha_3(t) \frac{R_3(\tilde{y}(t))}{2}. \tag{4}$$

with $\mathrm{N}_{3,x}(t)$ the number of individuals of sex x at the start of time t, $Z_3(t)$ the total mortality at time t, $\alpha_3(t)$ the fraction of the annual recruitment during time t, and $R_3(\tilde{y}(t))$ the recruitment[3] during the 'biological' year $\tilde{y}(t)$ of blue endeavour prawns.

Recruits in the fishery $R_s(\tilde{y}(t) + 1)$ for species $s = 1, 2, 3$ during a 'biological' year $(\tilde{y}(t) + 1)$ are assumed to be related to the spawning stock size index $\mathrm{S}_s(y(t))$ of species s for the year $y(t)$, according to a Ricker stock-recruitment relationship fitted assuming temporally correlated environmental variability and down-weighting recruitments, as described in AppendixA.2.

The spawning stock size index $\mathrm{S}_3(y(t))$ of blue endeavour prawn for the year $y(t)$ is given by:

$$\mathrm{S}_3(y(t)) = \frac{1}{52} \sum_{t=52\left(y(t)-1\right)+1}^{52y(t)} \beta_3(t) \frac{1 - \exp\left(-Z_3(t)\right)}{Z_3(t)} \mathrm{N}_{3,\female}(t). \tag{5}$$

Parameter $\beta_3(t)$ is defined as for the size-structured model in section 2.1.1.

2.1.3. *White banana prawn: an uncertain resource*

Abundance of white banana prawns (species $s = 4$) appears to be more heavily influenced by the environment than by fishing pressure (Die and Ellis, 1999, Venables et al., 2011) and its year to year availability is highly variable. More specifically, stocks are strongly influenced by weather patterns, generally peaking in years in which there has been high rainfall. In the present study, white banana prawn annual biomass is modelled as a uniform i.i.d. random variable:

$$B_4(y(t)) \rightsquigarrow \mathcal{U}(B_4^-, B_4^+), \tag{6}$$

with $B_4(y(t))$ the stochastic biomass of white banana prawn for the year $y(t)$, and B_4^- and B_4^+ the uniform law bounds.

2.2. *Fishing mortality and catch*

Fishing mortalities $F_{s,l,f}(t)$ due to fishing effort of sub-fishery f ($f = 1$ for grooved tiger prawn sub-fishery and $f = 2$ for brown tiger prawn sub-fishery) on animals of species $s = 1, 2$ (grooved and

[3] the sex-ratio of the recruits is assumed to be 50:50 in the absence of data (Punt et al., 2011).

brown tiger prawns) in size-class l during time t and average fishing mortality $F_{3,f}(t)$ on animals of species $s = 3$ (blue endeavour prawn), are given by:

$$\begin{cases} F_{s,l,f}(t) = u(\mathrm{E}_f(t)), & s = 1,2 \quad \text{and} \quad f = 1,2 \\ F_{3,f}(t) = v(\mathrm{E}_f(t)), & s = 3 \quad \text{and} \quad f = 1,2. \end{cases} \tag{7}$$

Fishing mortality functions u and v are detailed in AppendixA.3.

Weekly catches $Y_{s,l,f}(t)$ of grooved ($s = 1$) and brown tiger prawns ($s = 2$), by size-class l and weekly catches $Y_{3,f}(t)$ of blue endeavour prawns ($s = 3$) by the grooved and brown tiger prawn fishing strategies ($f = 1, 2$); and annual catches $Y_{4,3}(y(t))$ of white banana prawns ($s = 4$) by the banana prawn sub-fishery ($f = 3$) are defined as in the system of equations 8:

$$\begin{cases} Y_{s,l,f}(t) = \sum_x \upsilon_{s,x,l} \mathrm{N}_{s,x,l}(t) F_{s,l,f}(t) \dfrac{1 - \exp\left(-M_s - \sum_{f=1,2} F_{s,l,f}(t)\right)}{M_s + \sum_{f=1,2} F_{s,l,f}(t)} & s = 1,2 \quad \text{and} \quad f = 1,2 \\ Y_{3,f}(t) = \sum_x \tilde{\upsilon}_{3,x} \mathrm{N}_s(t) F_{3,f}(t) \dfrac{1 - \exp\left(-M_3 - \sum_{f=1,2} F_{3,f}(t)\right)}{M_3 + \sum_{f=1,2} F_{3,f}(t)} & f = 1,2. \\ Y_{4,3}(y(t)) = q_{4,3} B_4(y(t)) \mathrm{E}_3(y(t)) \end{cases} \tag{8}$$

with $\upsilon_{s,x,l}$ the mass of an animal of species s ($s = 1, 2$) and sex x in size-class l, and $\tilde{\upsilon}_{3,x}$ the average mass of a blue endeavour prawn of sex x.

2.3. *Economic component*

2.3.1. *Fishing income*

The annual gross incomes of the tiger prawn fishing strategies (f=1,2) and banana prawn sub-fishery (f=3) are calculated as described by the set of equation (9):

$$\begin{cases} \mathrm{Inc}_f(y(t)) = \displaystyle\sum_{t=52\left(y(t)-1\right)+1}^{52y(t)} \left(\sum_{s=1,2} \sum_l p_{tig,l}(y(t)) Y_{s,l,f}(t) + p_3(y(t)) Y_{3,f}(t) \right), & f = 1,2. \\ \mathrm{Inc}_3(y(t)) = p_4(y(t)) Y_{4,3}(y(t)), \end{cases} \tag{9}$$

Grooved and brown tiger prawns are marketed together as 'tiger prawns' under a common size- and time-dependent price, where $p_{tig,l}(y(t))$ is the average market price per kilogram for animals in size-class l (related to five market categories) during the year $y(t)$. The average price per kilogram of blue endeavour and white banana prawns is denoted $p_{s=3,4}(y(t))$ and is also time-, but not size-dependent.

2.3.2. Fishing costs

Variable costs $C_f^{var}(t)$ for the sub-fishery f during time t, and annual fixed costs by vessel C_v^{fix} are detailed in equation (10):

$$\begin{cases} C_f^{var}(t) = \mathrm{c}^L \mathrm{Inc}_f(t) + \mathrm{c}^M \sum_{s=1}^{4} Y_{s,f}(t) + \left(\mathrm{c}_f^K + \mathrm{c}_f^F(y(t))\right)\mathrm{E}_f(t) \\ C_v^{fix} = W_v + (\mathrm{r} + d)\psi_v \end{cases} \tag{10}$$

where c^L is the share cost of labour (crew are paid a share of the income) and c^M is the cost of packaging and gear maintenance (assumed to be proportional to the fishery catch in weight). Unit costs c_f^K and $\mathrm{c}_f^F(y(t))$ are respectively the cost of repairs and maintenance and the cost of fuel and grease per unit of effort of sub-fishery f during the year $y(t)$. The values of these costs are assumed constant across grooved and brown tiger prawn fishing strategies but differ between tiger and banana prawn sub-fisheries. W_v are the annual vessel costs (i.e. those costs are not related to the level of fishing effort), r is the opportunity cost of capital and is assumed equal to the discount rate, set at 5 % following Punt et al. (2011), d is the economic depreciation rate and ψ_v is the average value of capital by vessel.

2.3.3. Annual profit and net present value

The total annual profit $\pi(y(t))$ for the entire NPF for year $y(t)$ is given by:

$$\pi(y(t)) = \sum_{f=1}^{3}\left(\mathrm{Inc}_f(y(t)) - \sum_{t=52\left(y(t)-1\right)+1}^{52y(t)} C_f^{var}(t)\right) - C_v^{fix}\mathrm{K}(y(t)). \tag{11}$$

where $\mathrm{K}(y(t))$ is the number of vessels involved in the NPF during the year $y(t)$.

The net present value (NPV) of the flow of profits over simulation time is calculated as the aggregated value of discounted annual profits as in Punt et al. (2010) and is given by:

$$\mathrm{NPV} = \sum_{y(t)=1}^{T-1} \frac{\pi(y(t))}{(1+\mathrm{r})^{y(t)-1}} + \frac{[\pi(T)/\mathrm{r}]}{(1+\mathrm{r})^{T-1}}. \tag{12}$$

where r is the discount rate, and $\pi(T)$ is the level of profit during the terminal year of the simulation.

2.4. Parameter estimation

Dichmont et al. (2003) and Punt et al. (2010) describe the approaches used to estimate parameter values for the dynamic population models. The impact of parameter uncertainty was explored in Punt et al. (2010). A non-linear least-squares method was used for the estimation of the parameters (B_4^-,B_4^+ and $q_{4,3}$) related to white banana prawn by fitting observed data (c.f. C.2) of white banana prawn catches (in weight) and annual banana fishing effort over 17 years (1994 to 2010). The values of cost parameters (c^L, c^M, c^K_f, c^F_f, W_v and ψ_v) are derived from an economic survey of the fishery during 2007-2008 (Perks and Vieira, 2010) and were adjusted for known changes in input prices to provide estimates of the costs in 2009-2010 values. The depreciation rate was set as in Punt et al. (2010). All these cost and price assumptions were discussed with, and validated by industry representatives who were members of the NPF Resource Assessment Group (RAG)[4]. Base case values of all biological and economic parameters are given in AppendixB.

2.5. *Effort allocation strategy* $\mathrm{T}_{\text{adapt}}$

The total annual fishing effort $\mathrm{E}(y(t))$, for the entire NPF, is calculated by:

$$\mathrm{E}(y(t)) = e(y(t))\mathrm{K}(y(t)). \tag{13}$$

where $e(y(t))$ is the annual average effort per vessel for the year $y(t)$ expressed in number of days at sea and $\mathrm{K}(y(t))$ the number of vessels for that year. Exogenous technical constraints on $e(y(t))$ and $\mathrm{K}(y(t))$ are included in the model and maximal nominal effort per week set at 7 days.

To capture what happens currently in the NPF, this total annual fishing effort is allocated weekly between tiger and banana prawn sub-fisheries, but also between the two tiger prawn species through a simplified, three-steps, effort allocation model as shown in figure 3.

- Step 1: Distribution of tiger and banana prawn annual effort

  An abundant banana prawn year will result in a decrease of the proportion of the annual effort directed to the tiger prawns fishing. The allocation of the total annual fishing effort between tiger and banana prawns fishing therefore depends on white banana prawn annual biomass $B_{s=4}(y(t))$. The arrows (1) in figure 3 illustrate this allocation and the set of equations (14) gives the relationship between the annual banana prawns catch per unit effort (CPUE) and the annual proportion of tiger prawn effort ($f = 1 + 2$):

$$\begin{cases} \mathrm{E}(y(t)) = \mathrm{E}_{1+2}(y(t)) + \mathrm{E}_3(y(t)), & \\ \dfrac{\mathrm{E}_{1+2}(y(t))}{\mathrm{E}(y(t))} = a\mathrm{CPUE}_4(y(t)) + b, & s = 4. \end{cases} \tag{14}$$

  with $\mathrm{E}_{1+2}(y(t))$ the annual effort of tiger prawn sub-fishery and $\mathrm{E}_3(y(t))$ the banana prawn sub-fishery annual effort during the year $y(t)$. Details on CPUE are given in AppendixA.4. Param-

[4]The NPF Resource Assessment Group has responsibility for assessing the dynamics and status of NPF species. The group comprises fishery scientists, industry members, fishery economists, and the AFMA manager responsible for the fishery.

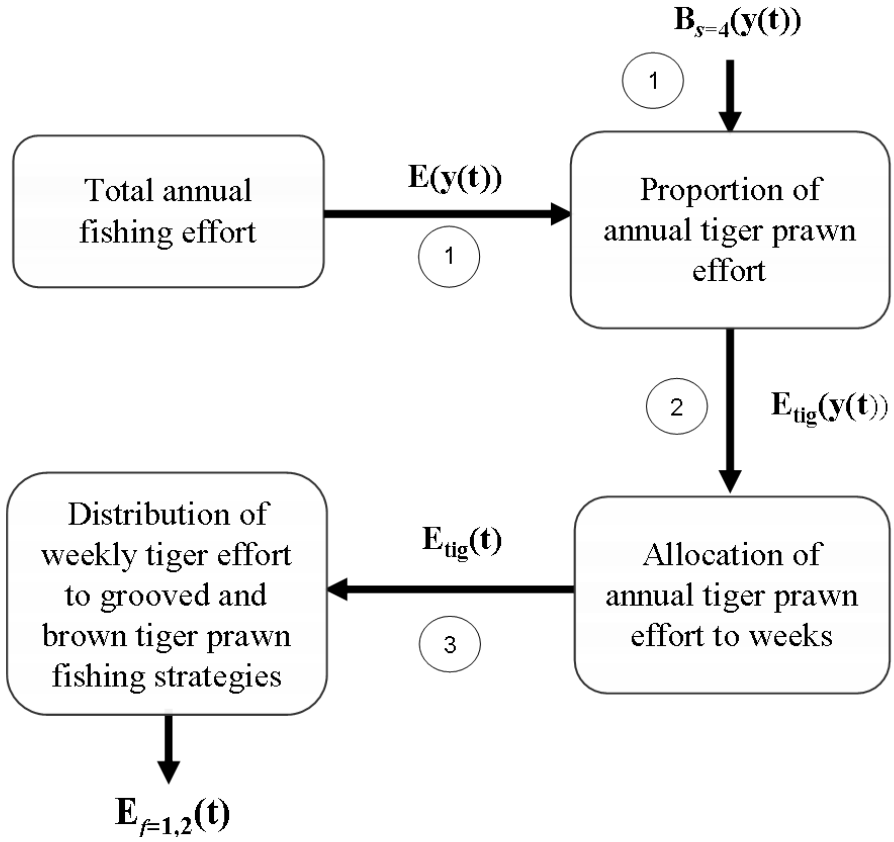


Figure 3: Flowchart of the algorithm used to determine the weekly effort (days at sea) during year $y(t)$ of grooved and brown tiger prawn fishing strategies ($f = 1, 2$), based on the total annual effort and white banana prawn annual biomass. The variables next to the arrows represent the output from one box and input into another box. The circles with numbers correspond to the three different steps of the algorithm.

eters a and b are estimated from a linear regression model using historical data from 1994 to 2010[5] which is displayed in figure C.2 in the appendix C.

- Step 2: Weekly tiger prawn sub-fishery effort allocation

  An empirical approach is taken to predict the weekly allocation of the tiger prawn sub-fishery effort for year $y(t)$. Because of the great variability of the various weekly effort patterns of the historical years, using a fixed weekly pattern is not relevant. Due to the influence of the season start dates and annual effort of banana prawn sub-fishery on the tiger prawn weekly effort patterns, the solution to randomly select a year among the historical years 1994 to 2010 is neither relevant. Sensitivity analyses of weekly patterns would thus be necessary, and would increase the number of simulations to run, increasing significantly the level of complexity of the model. For simplicity, a historical weekly pattern is selected between 1994 and 2010 for each

[5]Only historical data after 1994 are taken into account due to major changes in the fishery structure that occurred in that year.

year $y(t)$ according to the proportion of annual effort dedicated to the tiger prawn sub-fishery for the year $y(t)$ (i.e. depending on the white banana annual biomass simulated). This step is illustrated by the arrow (2) in figure 3. Appendix D details the algorithm on which depend the selection of the historical weekly pattern.

- Step 3: Grooved and brown tiger prawns fishing strategies effort allocation

  The final step of the effort distribution model (arrow (3) in figure 3) allocates the weekly tiger effort to the grooved and brown tiger prawns. This is achieved using a fixed pattern[6] $\Upsilon^{strat}(t \text{ modulo } 52)$ or proportion of weekly tiger prawn effort directed towards grooved prawns ($f = 1$) at time (t modulo 52). The effort by week directed towards grooved ($f = 1$) and brown ($f = 2$) prawns is described by equation (15):

$$\begin{cases} \mathrm{E}_{1+2}(t) = \mathrm{E}_1(t) + \mathrm{E}_2(t), \\ \mathrm{E}_1(t) = \Upsilon^{strat}(t \text{ modulo } 52)\mathrm{E}_{1+2}(t). \end{cases} \tag{15}$$

This full effort allocation model corresponds to an 'adaptive' effort allocation strategy ($\mathrm{T}_{\text{adapt}}$) which currently reflects the situation in the NPF. The resulting proportion of total annual effort directed to the tiger prawns ranges between 60 and 76%.

2.6. *Other effort allocation strategies*

In this paper, the economic performance of the NPF is compared under various effort allocation strategies characterised by the proportion of effort allocated to the different sub-fisheries, namely more or less effort allocated to tiger or banana prawn sub-fisheries. Consequently the strategies also contrast in terms of the resulting weekly effort patterns of tiger and banana prawn fishing (calculated as described in section 2.5). In addition of the $\mathrm{T}_{\text{adapt}}$ effort allocation strategy presented in section 2.5, six other strategies (detailed in table 1) are studied and correspond to alternative 'specialisation effort allocation' strategies in which the annual proportion of total effort allocated to tiger prawns is pre-defined and hence no longer depends on banana prawn biomasses. Therefore under these six alternative effort allocation strategies, only the last two steps of the effort allocation model are applied. Three 'banana specialisation' effort allocation strategies (T_0, T_{10} and T_{20}) consist of setting the annual proportion of tiger prawn effort to 0%, 10% and 20% of total annual effort. Two 'tiger specialisation' effort allocation strategies (T_{90} and T_{100}) involve allocating 90% and 100% of the annual effort to

[6]The values of $\Upsilon^{strat}(t)$ correspond to the predicted proportion of tiger prawn effort directed towards the grooved prawns during week (t modulo 52) in 2010 derived from the CSIRO operating model.

the tiger prawn sub-fishery. Finally a 'balanced' effort allocation strategy (T_{50}) is analysed; in which total annual effort is split equally between the two sub-fisheries. Because of policy and technical constraints, the pattern of open and closed weeks is set to that which occurred in 2010 (i.e. with respect to the mid-season closure).

Table 1: Effort allocation strategies (in each row) considered in this study. The strategies differ in the annual effort $E_{1+2}(y(t))$ allocated to tiger prawn sub-fishery.

Allocation strategies	Description	Annual effort of tiger prawn sub-fishery
T_0	annual proportion of tiger prawn sub-fishery effort sets to 0%.	$E_{1+2}(y(t)) = 0$
T_{10}	annual proportion of tiger prawn sub-fishery effort sets to 10%.	$E_{1+2}(y(t)) = 0.1E(y(t))$
T_{20}	annual proportion of tiger prawn sub-fishery effort sets to 20%.	$E_{1+2}(y(t)) = 0.2E(y(t))$
T_{50}	annual proportion of tiger prawn sub-fishery effort sets to 50%.	$E_{1+2}(y(t)) = 0.5E(y(t))$
T_{adapt}	'adaptive' effort allocation strategy.	see equations (14) and (15)
T_{90}	annual proportion of tiger prawn sub-fishery effort sets to 90%.	$E_{1+2}(y(t)) = 0.9E(y(t))$
T_{100}	annual proportion of tiger prawn sub-fishery effort sets to 100%.	$E_{1+2}(y(t)) = E(y(t))$

2.7. *Fishing capacity management strategies*

We assess the effects of changes in fishing capacity using four strategies regarding management of fishing capacity, defined in terms of the number of vessels $K(y(t))$ and days at sea per vessel $e(y(t))$. Table 2 summarizes the four fishing capacity strategies.

Table 2: Fishing capacity strategies (in each row).

Annual effort settings	Description
SQ	$K(y(t))$=52 vessels and $e(y(t))$=162 days at sea per vessel
e^+	$K(y(t))$=52 vessels and $e(y(t))$=196 days at sea per vessel
K^+	$K(y(t))$=78 vessels and $e(y(t))$=162 days at sea per vessel
K^-	$K(y(t))$=26 vessels and $e(y(t))$=162 days at sea per vessel

The status quo fishing capacity strategy SQ corresponds to an annual number of vessels and total annual effort equal to the values observed in 2010, i.e. $K(y(t))$=52 and $e(y(t))$=162. Under fishing capacity strategy e^+ the number of vessels remains at its 2010 level but annual effort per vessel is increased to that allowed by the maximum number of open weeks (28 weeks). Therefore the annual effort per vessel for the e^+ fishing capacity strategy is set to 196 days at sea. Fishing capacity strategy K^+ incorporates an increase in the annual number of vessel by 50% but leaves the average effort per vessel unchanged, i.e. $K(y(t))$=78 and $e(y(t))$=162. Similarly strategy K^- represents a 50% decrease in the annual number of vessels whereas no change in the average effort by vessel, i.e. $K(y(t))$=26 and $e(y(t))$=162.

2.8. *Economic scenarios*

The key economic outputs from the bio-economic model are the annual profit for the entire NPF and the associated net present value, all of which are sensitive to assumptions about the values of biological and economic parameters described in section 2.4. Sensitivity to economic parameters is explored through the analysis of scenarios incorporating different assumptions about changes in fuel and prawn prices. All other economic parameters were assumed to remain constant over the simulation period. We report results for only two economic scenarios[7], these being a 'base case' scenario (BC) and a 'most likely' scenario (ML) detailed in table 3.

Table 3: Economic scenarios (in each row) considered in this study.

Scenarios	Description
BC	Base case scenario: constant prawn and fuel prices
ML	Most likely scenario: prawn prices decrease by 3% per year and fuel price increases by 5% per year

The BC scenario assumes that prawn and fuel prices remain constant at their estimated 2010 levels over the simulation period. Variable and fixed costs are set to the average values estimated for the 2010-2012 period. The ML scenario represents a most likely evolution over the simulation period of key economic parameters for this fishery. Except for banana prawn[8], the main market for NPF prawns is Asia (especially Japan), and the price received is largely dependent on the Yen-AU$ exchange rate and the total supplies to this market (Punt et al., 2010). Therefore prawn prices are assumed to be independent of the landings of our model. Based on historical trends, the most likely scenario assumes a progressive prawn prices annual decrease of 3%. In this scenario fuel price is assumed to follow a progressive increase of 5% per year. Assumption of fuel price evolution is supported by a linear model from historical data given in figure C.1 in the appendix C.

The biological and economic performances of the fishery for the seven effort allocation strategies, the four fishing capacity strategies and under the two economic scenarios are analysed accounting for the stochastic nature of the model (i.e. environmental variabilities applied to annual recruitments of tiger and blue endeavour prawns and to white banana prawn annual biomasses). For every combination of effort allocation, fishing capacity strategies and economic scenarios, 1000 trajectories are simulated over a 10 year period from 2010. Each trajectory represents a possible state of nature for

[7]We tested different combination of scenarios including increase and decrease of prawn and fuel prices.

[8]Until recently the main market for banana prawns was also Asia, however most of banana prawns are sold now in domestic market.

each year of the simulation, $\omega(.) = (\omega_1(.),\omega_2(.), \omega_3(.),\omega_4(.))$; which stands for the set of annual recruitments of tiger and blue endeavour prawns as detailed in Punt et al. (2011) and annual biomasses of white banana prawns in equation (6). The different $\omega_i(.)$ are assumed to be independent by species. Each combination of strategies and scenarios is simulated with the same set of $\omega(.)$. The numerical implementations and computations of the model have been carried out with the scientific software SCILAB[9].

3. Results

Economic performance of the fishery is studied through the mean value and variance of annual profit for the entire NPF and the NPV of the fishery.

3.1. Sensitivity of biological and economic performance indicators to economic scenarios

Figure 4 shows the evolution of the spawning stock size indices over the simulation period, for each of the three exploited tiger and blue endeavour prawns with the 'adaptive' effort allocation (T_{adapt}) strategy, reflecting the current situation of the fishery, and with the status quo (SQ) fishing capacity strategy. The most likely (ML) economic scenario being an economic scenario, there are no differences between the biological outputs under base case and most likely scenarios. Therefore a common output is displayed in figure 4. Figure 5 displays the evolution of the total annual profit over the simulation period with the T_{adapt} allocation strategy and SQ fishing capacity strategy, for the BC (figure 5(a)) and the ML (figure 5(b)) economic scenarios.

According to figure 4, the size of the spawning stocks remains relatively stable for both grooved tiger and blue endeavour prawns over the ten-year period to 2020 (with an average increase of 5% and 16%, respectively), while the evolution of the brown tiger prawn spawning stock size index shows an average decline of 32%.

Under the BC scenario the model predicts sustained positive profit throughout the simulation period (figure 5(a)), except for 0.7% of the trajectories for which the annual profit is negative during at least one year of the simulation. Although positive profits are predicted, in 63.7% of trajectories, the annual profit will fall short of its 2010 reference level for at least one year of the simulation. Comparison of figures 5(a) and 5(b) shows that the economic performance of the fishery will deteriorate

[9] SCILAB is a free software http://www.scilab.org/ dedicated to engineering and scientific calculus. It is especially well-suited to deal with dynamic systems and control theory.

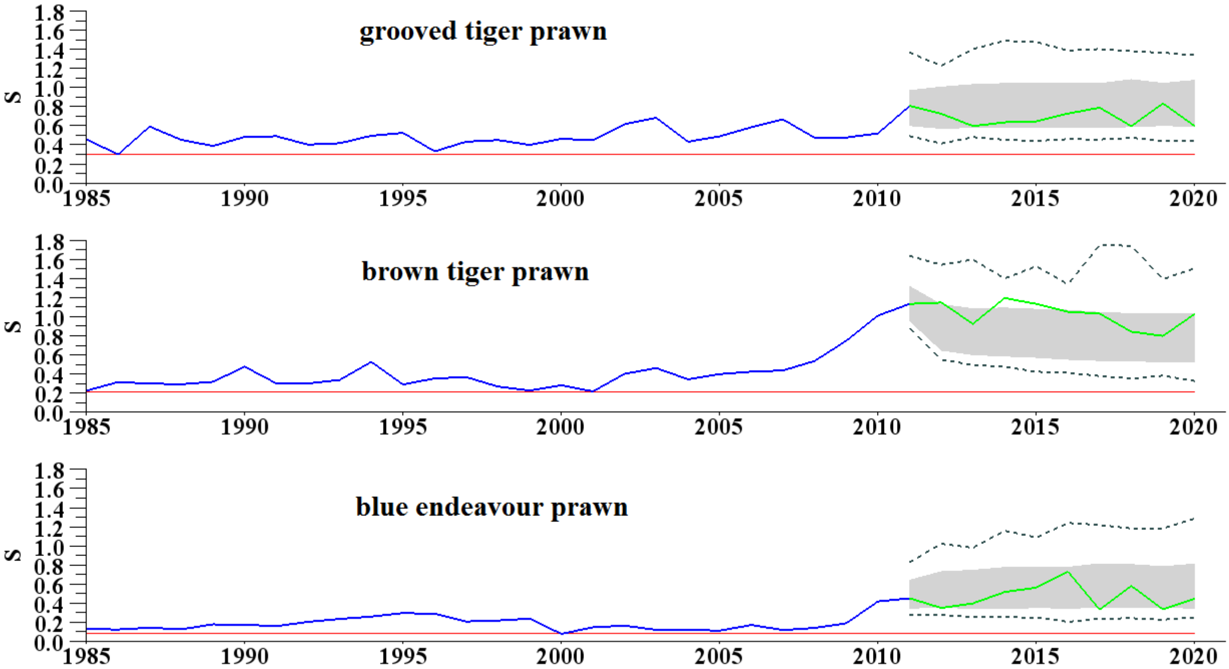
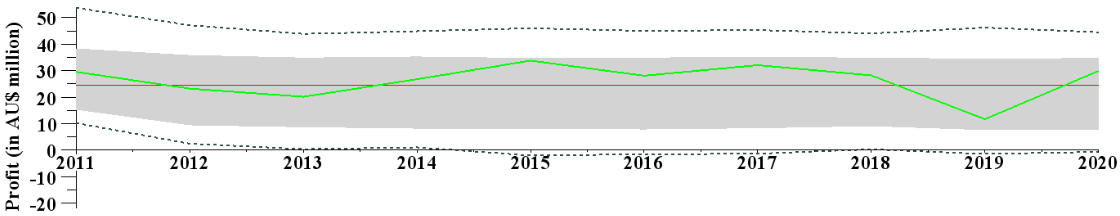
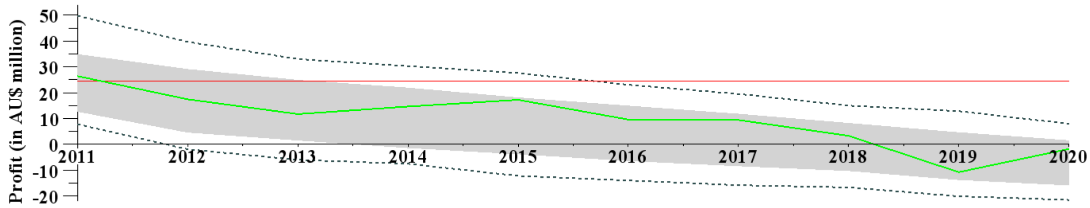


Figure 4: Trajectories over 10 years of the spawning stock size indices $S_s(y(t))$ of grooved, brown tiger and blue endeavour prawns with the T_{adapt} allocation strategy and SQ fishing capacity strategy. These outputs are similar under both BC and ML economic scenarios. In each sub-figure the blue line corresponds to the historical spawning stock size indices estimated for the past 25 years before the reference year 2010, the red line represents the historical minimal spawning stock size index by species, the dotted dark lines represent the field of possibilities that includes all of the 1000 simulated trajectories and the grey field includes 95% of these trajectories. The green line corresponds to a randomly selected trajectory among the 1000 trajectories associated to the same set of recruitments and banana biomasses $\omega(.)$ for each sub-plot of figures 4 and 5.

substantially under the ML economic scenario. Indeed given the projected decrease in market prices and increase in fuel price, 52.2% of the trajectories will have a negative annual profit for at least one year of the simulation. Moreover, there is 91.4% chance that the annual profit will be negative by the last year of the simulation compared to only 0.1% under the base case scenario. Furthermore there is a 100% chance that the profit will be below its 2010 reference level by 2020 (versus 68.3% probability with a base case scenario). The mean value of the reduction in the NPV of the NPF between the base case and most likely scenario is AU$ 463 million.



(a) $\pi(y(t))$ under a base case scenario BC.



(b) $\pi(y(t))$ under a most likely scenario ML.

Figure 5: Trajectories over 10 years of the total annual profits $\pi(y(t))$ with a T_{adapt} allocation strategy and a status quo fishing capacity strategy SQ for a base case scenario BC in (a) and a most likely scenario ML in (b). In each sub-figure the red line corresponds to the annual profit estimated for the reference year 2010, the dotted dark lines delimit the field of possibilities that includes all of the 1000 simulated trajectories and the grey field includes 95% of these trajectories. The green line corresponds to a randomly selected trajectory among the 1000 trajectories associated to the same set of recruitments and banana biomasses $\omega(.)$ for each sub-plot of the figures 4 and 5.

3.2. *Mean-variance analyses*

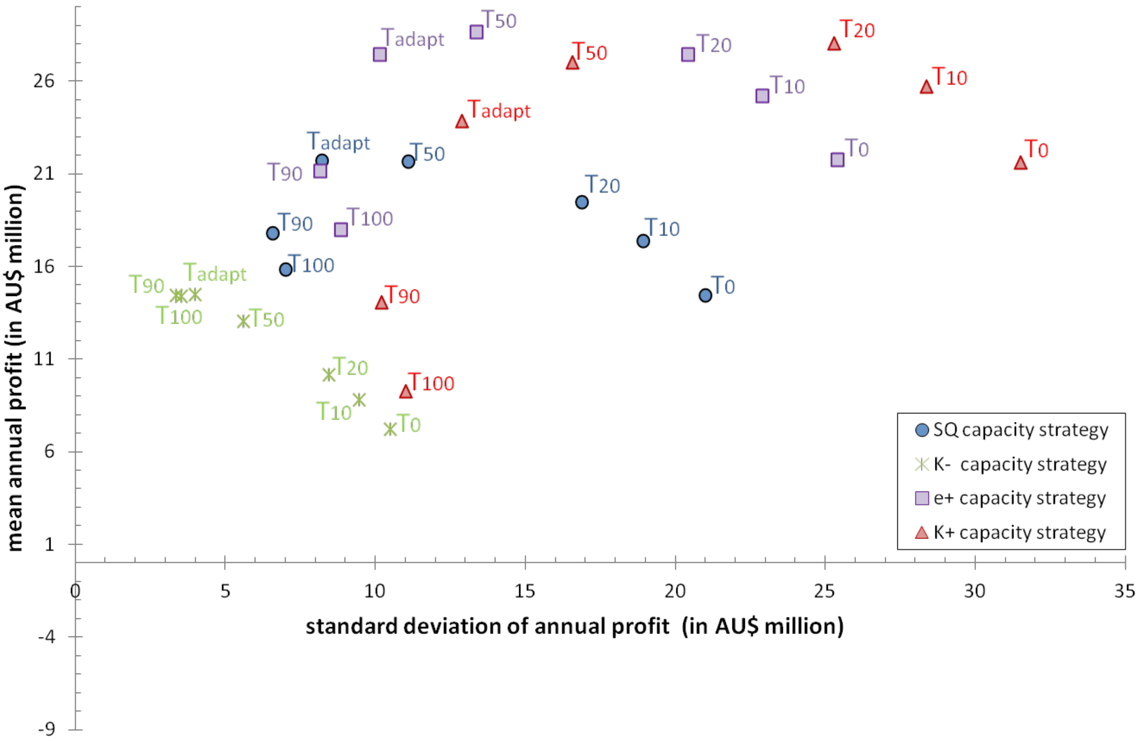
To study the trade-offs between the mean economic performance of the fishery and the variance of this performance under different economic and fishing management scenarios, mean-variance analyses are conducted.

Figure 6 represents the average annual profit of the fishery versus its standard deviation under a BC in (a) and a ML economic scenario in (b).

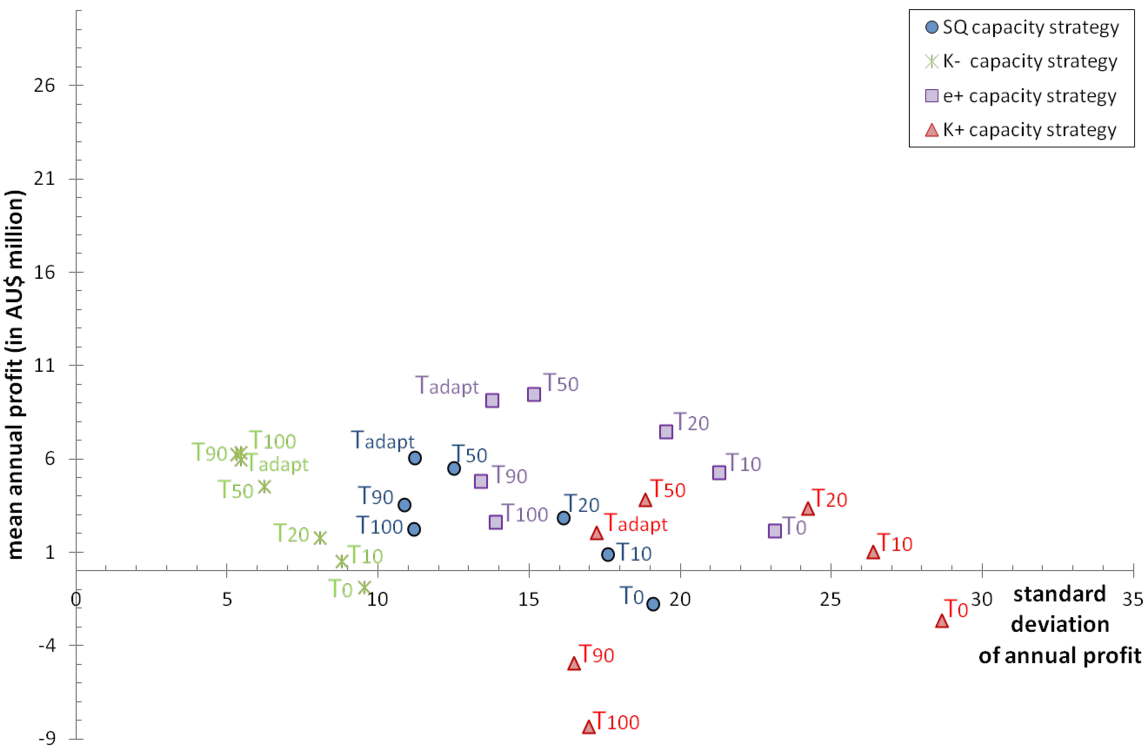
3.2.1. *Performance of various effort allocation strategies*

Results for the SQ fishing capacity strategy (blue dots in figure 6) show that strategies involving higher levels of specialisation (banana or tiger prawn sub-fisheries) are marked with reduced average annual profit under both economic scenarios. The average NPV of the fishery is higher with the balanced T_{50} and the 'adaptive' T_{adapt} effort allocation strategies (AU$ 434 and AU$ 429 million for the base case scenario, and - AU$ 46 and - AU$ 34 million for the most likely scenario). Importantly, the banana specialisation strategies are also associated with higher economic variability, compared to the tiger specialisation strategies, for both economic scenarios.

In Figure 7, the mean-variance analysis for the partial annual income coming from each of the



(a) Base case scenario



(b) Most likely scenario

Figure 6: Economic mean-variance analysis: each dot represents the average annual total profit $\pi(y(t))$ over the years and the 1000 trajectories simulated versus the standard deviation associated. In each sub-plot the results are featured by effort allocation strategy (T_{adapt}, T_0, T_{10}, T_{20}, T_{50}, T_{90} and T_{100}) under different fishing capacity strategies. The blue circles correspond to a status quo fishing capacity strategy SQ, the purple cross to an increase in effort per vessel e^+, the red triangles to an increase in the number of vessels K^+ and the green square to a decrease in the number of vessels K^-. Effort allocation and fishing capacity strategies are considered under a base case economic scenario in (a) and under a most likely economic scenario in (b).

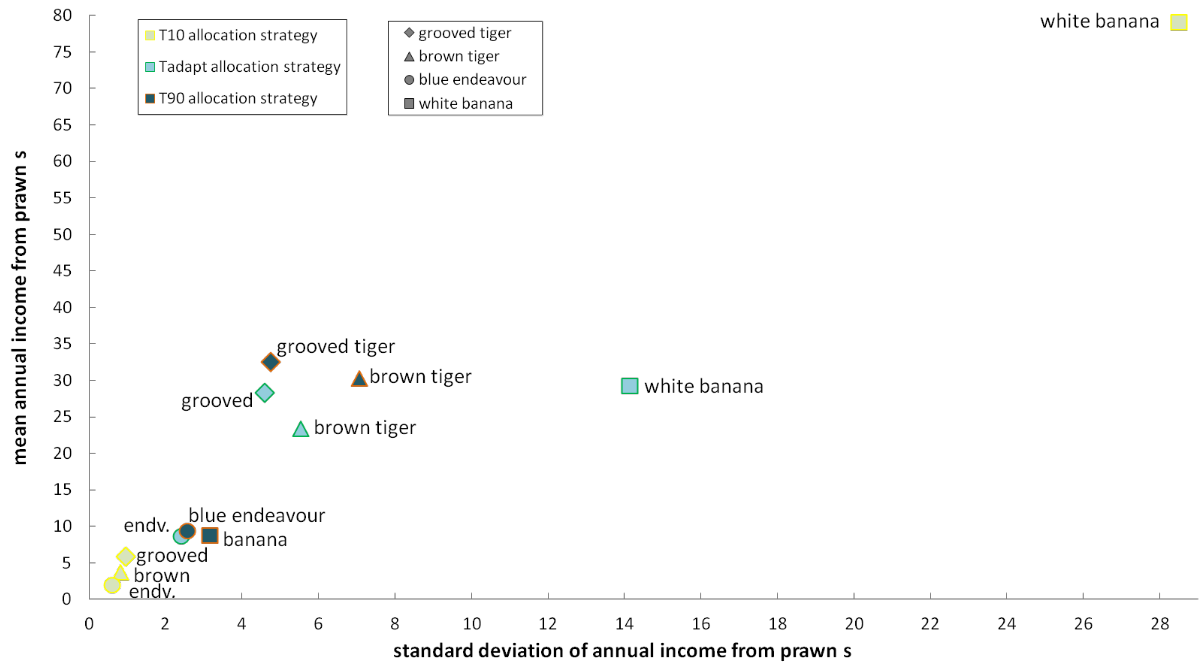


Figure 7: Mean-variance analysis of the partial total annual income coming from the four studied species: each dot represents the average over the mean annual income from species *s* (for all years and simulations) versus the standard deviation associated. Results are featured with the effort allocation strategy (T_{adapt}, T_{10} and T_{90}) in colours and the species are represented by different shapes of dots. The blue correspond to T_{adapt}, the red to T_{90} and the green to T_{10} allocation strategy. Whereas the diamonds represent the partial annual income coming from grooved tiger prawn catches, the triangles the ones coming from brown tiger prawn, the circles stand for blue endeavour prawn and the squares for white banana prawn. Effort allocation strategies are considered under a base case BC economic scenario and a status quo SQ fishing capacity strategy.

four targeted species with the SQ fishing capacity and BC economic scenarios is illustrated for three contrasting effort allocation strategies: T_{10}, T_{adapt} and T_{90}. This figure allows us to distinguish the part of the economic variability resulting from the biological variability of each exploited species, and that for the three contrasted allocation strategies. This figure shows that the difference observed in the economic variability between tiger and banana 'specialisation' strategies is mainly due to the biological variability of white banana prawn catches. Biological variabilities of tiger and endeavour prawns play, therefore, only a minor role in the total economic variability. Furthermore, the economic variability attributed to brown tiger prawn catches is greater than that arising from either grooved tiger or blue endeavour prawns for both the 'adaptive' and tiger effort allocation strategies.

3.2.2. *Performance of various fishing capacity strategies*

Comparison of economic performance for effort allocation strategies across alternative fishing capacity strategies (figure 6) shows a positive relationship between fishing capacity and economic variability.

The effort allocation strategies according to their mean NPV for each fishing capacity strategy and

Table 4: Rank of the effort allocation strategies (in row) according their mean NPV values (1 being the strategy with the highest average NPV) for each level of fishing capacity and economic scenario (in column). Fishing capacity strategies are sorted in increasing order of fishing capacity.

		BC				ML			
		increase in fishing capacity ⟶				increase in fishing capacity ⟶			
	Strategies	K^-	SQ	e^+	K^+	K^-	SQ	e^+	K^+
incr. of pressure on tiger prawns ↓	T_0	7	7	5	5	7	7	7	5
	T_{10}	6	4	4	3	6	6	4	4
	T_{20}	5	3	2	1	5	4	3	2
	T_{50}	4	1	1	2	4	2	1	1
	T_{adapt}	1	2	3	4	3	1	2	3
	T_{90}	2	5	6	6	2	3	5	6
	T_{100}	3	6	7	7	1	5	6	7

economic scenario are ranked in Table 4, with 1 indicating the most profitable in terms of fishery-wide NPV. Under the BC economic scenario the more fishing capacity increases, the better the banana specialisation strategies perform relative to the tiger prawn specialisation strategies (Table 4 and figure 6). Moreover, effort allocation strategies that involve higher tiger prawn specialisation perform relatively better, as compared to strategies where effort is directed more towards the banana prawn sub-fishery, when the ML economic scenario is considered. Furthermore, the highest mean NPV among all effort allocation strategies under the BC scenario occurs with a K^+ fishing capacity strategy and the T_{20} effort allocation strategy, while under the ML scenario, it is obtained with a K^- fishing capacity strategy and a T_{100} effort allocation strategy.

4. Discussion

4.1. The interest of an integrated bio-economic model

The simplified bio-economic model of the NPF presented in this article is based on the synthesis of a complex set of models developed in support of the Management Strategy Evaluation (MSE) approach to managing this fishery (Dichmont et al., 2006, 2008, Venables et al., 2009). The model allows for the explicit representation of the tiger prawn sub-fishery targeting more predictable species, and the banana prawn sub-fishery targeting less predictable species. Prawns are short-lived species (i.e. 1-2 years life cycle) and their dynamics are expressed at a weekly time-step which allows representation of intra-annual and seasonal biological processes such as spawning and recruitment, and economic processes such as seasonal allocation of fishing effort, as is advocated by Anderson and Seijo (2010). While many features of the original models have been simplified, key aspects of model structure have been maintained where these were considered crucial to the understanding of the bio-economic system under study.

We use this model to compare the bio-economic performances of a range of fishing capacity strategies involving variations in number of vessels and annual effort per vessel, using mean variance analysis. Sensitivity of the results to variations in the economic conditions of the fishery, and to different effort allocation strategies incorporating varying degrees of specialisation is also explored. Based on the simulation results, the adaptation options available to the fishery can therefore be examined.

4.2. Trade-off between mean annual levels of profit and their variability

Previous studies contributed to setting the current number of vessels in the fishery to 52 vessels, by establishing this as the number required to achieve Maximum Economic Yield (MEY). Based on our simulations, it appears that the NPF currently operates with an effort allocation strategy allowing the best compromise between mean performance and variability in this performance, as is illustrated by the status quo fishing capacity simulation results for the 'adaptive' effort allocation strategy (where the fishery adapts its effort allocation to white banana prawn biomasses) (figure 6(a)). In addition, as illustrated in figure 6(a), the simulated fishery could achieve higher levels of average economic performance with this 'adaptive' effort allocation strategy, by adopting a fishing capacity strategy allowing a higher level of effort per vessel or a larger number of vessels. However, this would be obtained at the cost of increased economic risk, as illustrated by the higher inter-annual variability in profits under these strategies. When considering an increase of annual effort per vessel, the fishery could get even higher mean annual profit with a strategy allocating the same amount of effort towards both tiger and banana prawn sub-fisheries, but it would be at cost of about a 37% increase in the variance of simulated profit compared to an 'adaptive' effort allocation strategy. The difference in mean annual profit is even stronger with effort allocation strategies focusing effort more on banana prawns (T_{10}, T_{20} and T_{50}; see figure 6(a)) when status quo fishing capacity is compared with increased fishing capacity or annual effort per vessel. While these strategies all lead to average annual profits that are higher than with the status quo fishing capacity strategy and T_{adapt} allocation strategy, they also entail much higher levels of inter-annual variability in profits. On the other hand, if the fleet is targeting mainly tiger prawns (T_{100} and T_{90}), compared to alternative effort allocation strategies both the mean economic performance of the fishery and the inter-annual economic variability will decrease and there will also be a strong negative impact on mean spawning stock levels (as shown in the supplementary data). The difference in economic variability between tiger and banana specialisation allocation strategies derives mainly from differences in the biological variability of white banana prawn stocks, as exhibited in figure 7.

The model illustrates an important aspect of managing mixed fisheries for MEY, namely that given the biological variability of some of the target resources, increased average profits may be associated with increased variability in these profits. In cases where industry are risk averse, this may lead to management options with lower levels of performance, but with reduced economic risk, being preferred. Risk aversion of key stakeholders (fishers, industry, and more broadly, society) should therefore be included in the evaluation of management strategies. As Mistiaen and Strand (2000) pointed out, it is widely agreed that fisher's risk preference is a major determinant of their responses to various changes in fishing stock, market, and weather conditions. Therefore, it is important to integrate fisher's risk preference in modelling and analyse their decision-making behaviour (Nguyen and Leung, 2009). Results of the case study considered here, allow identification of an implicit risk aversion measure, which, for a given effort allocation strategy, can be estimated as the difference between the mean annual profits under the current fishing capacity strategy SQ and the fishing capacity strategy which maximises mean annual profits.

The NPF operates under a strong co-management structure. Nearly all of the industry is incorporated into a single company, which is represented in the management decision process. Industry have a direct role in determining annual effort targets (based on bio-economic advice), and was also involved in setting the number of vessels to achieve MEY. Management and industry objectives can be considered therefore relatively aligned (Pascoe et al., 2009). Thus the risk aversion of the fishery, can be estimated by the managers risk aversion which corresponds to difference between the mean annual profits under the current fishing capacity strategy SQ and the increase of alternative vessels strategies. This is approximately AU\$ 2.17 million, or 10% of the average annual profits. Managers (or in this case industry) are willing to forgo AU\$ 0.47 million in average annual profit to reduce the standard deviation of profit by one million. However, the choice of annual effort per vessel and allocation of fishing effort between prawn sub-fisheries relies mainly on fishers. Therefore, fishers' risk aversion can be estimated by the difference between the mean annual profits under the T_{adapt} allocation strategy with the current effort per vessel SQ and the combination of allocation strategy and level of effort per vessel which maximises mean annual profits (i.e. T_{50} allocation strategy and e^{+} capacity strategy). This value is estimated at AU\$ 6.97 million, or 32% of the average annual profits. This implies that fishers are therefore willing to forgo AU$ 1.35 million in average annual profit to reduce the standard deviation of profit by one million.

An intermediate adaptation option could increase the effort per vessel from 162 to 196 days at sea, while keeping an 'adaptive' effort allocation strategy with 52 vessels. Indeed this combination gives an AU$ 2.99 million of supplementary profit per million of supplementary standard deviation of profit, which could be considered as a good compromise between increase of the average economic performance and increase of economic variability. Moreover, with this management option, impacts on tiger and endeavour prawn species are reduced compared to tiger prawn specialisation strategies (c.f. supplementary data).

4.3. *Expected effects of economic scenarios on the biological and economic performance of the fishery, and possible adaptation options*

Analyses of economic performance of the fishery under different economic scenarios illustrate the importance of sensitivity analyses to key economic parameters in bio-economic assessments. Whereas it is difficult to predict the future evolution of prices and costs as they are influenced principally by external drivers, scenarios and projections based on the best available knowledge of these drivers show that the fishery is likely to encounter strong economic difficulties, with average annual profit levels expected to be low and even negative in some periods.

The simulation results under the most likely economic scenario (figure 6(b)) show that management strategies aiming at increasing the fleet size, given current costs per vessel, would fail to improve fishery performance, in terms of both mean levels of performance, and variability of this performance. Possible adaptation strategies involve maintaining 'adaptive' effort allocation strategies, and either reducing fleet size below its historical level, or maintaining the fleet size but increasing the fishing effort per vessel. The first option provides levels of overall annual profits comparable to those obtained under the status quo fishing capacity strategy, but with reduced variability. Given the reduced number of vessels, individual performance of vessels would remain relatively high under this strategy. The latter option allows an increase in the average economic performance of the fleet, but at the cost of increased variability in performance, or economic risk.

Increase in fuel prices leads to a relatively more important increase in variable costs for the banana prawn sub-fishery, compared to the tiger prawn sub-fishery, as the banana prawn sub-fishery uses a greater amount of fuel per effort unit. Therefore, the most likely economic scenario appears to favour tiger prawn specialisation strategies.

Possible adaptive responses from fishers to the increased economic vulnerability predicted under a most likely economic scenario involve combinations of changes in fishing capacity and effort allocation strategies. Our analyses show that to maximize the mean economic performance, the best combination would likely involve a 'balanced effort allocation' strategy (where the fishery allocates equally its annual effort between tiger and banana prawns) with 52 vessels, but with an increase in the effort per vessel from 162 to 196 days at sea. However, this begs the question as to why the industry did not increase effort when prices were higher and variable costs lower, in which case even greater profits would have been realised. If the objective is to minimize the economic variability of annual profit, a more realistic adaptation option could be to allocate a substantial proportion of the total annual effort to the tiger prawn sub-fishery and reduce the number of vessels.

4.4. Perspectives

While the results obtained are specific to the case study considered in this analysis, the methods proposed would apply to any mixed fishery where information allows calibration of a dynamic bio-economic model of fishing across a range of species presenting different levels of natural variability. It is likely that most of the mixed fisheries in the world would be subject to similar trade-offs between average economic performance and variability of this performance from year to year. If this is the case, we argue that the question of variability in returns of a fishery should also be considered when discussing the identification of management strategies aimed at MEY. This would of course pose the question of the degree of risk aversion of key stakeholders, including industry, the fishers, and more broadly, society.

Fisheries management increasingly acknowledges that fish population dynamics are complex and influenced by factors that are usually poorly understood. This is the case with the white banana prawn dynamics. It may be that the conclusions of our analysis would change if the patterns of variability in abundance of banana prawns changed, due for example to changes in the environmental drivers which determine its year-to-year fluctuations in abundance. In particular, rainfall and sea level rise have been identified by Hobday et al. (2008) as key impacts of climate change in the NPF region, which may have an impact on the dynamics of the different species targeted by the NPF, notably on white banana prawn abundance. Climate change projections for rainfall are highly uncertain; rainfall is projected to decrease across parts of northern Australia with some areas showing a slight increase which may have a positive impact on white banana prawn catches (Hobday et al., 2008). Climate change may also have an impact on seagrass beds and mangrove forests, which are important nursery grounds for tiger prawns and banana prawns, respectively (Sands, 2011). Coupling this model with projections derived from models relating climate change to the environmental drivers of prawn abundance could therefore allow a more informed evaluation of the likely trade-offs between mean performance and economic risk in this fishery.

Finally, while our analysis has focused exclusively on the bio-economic trade-offs associated with species with commercial value, another key dimension of mixed fisheries which may also need to be considered in evaluating options is the impacts of effort allocation strategies on bycatch species of low commercial value, as well as on threatened, endangered and protected species and on habitats (Woodhams et al., 2011). Different levels of fishing capacity and alternative effort allocation strategies, impacting differently on the surrounding ecosystem, will potentially lead to different outcomes in terms of the ecological impacts of fishing. This will be the focus of further research using the bio-economic model presented in this article.

Acknowledgement

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Appendix A: Dynamics details of the bio-economic model

AppendixA.1. Tiger prawn abundance dynamics

The population dynamics of grooved and brown tiger prawns ($s = 1, 2$, respectively) are based on a sex and size-structured model relying on a weekly time-step and governed by the equation (A.1) as in Punt et al. (2010).

$$\vec{\mathrm{N}}_{s,x}(t+1) = \mathbf{X}_{s,x}\mathbf{Suv}_s(t)\vec{\mathrm{N}}_{s,x}(t) + \alpha_s(t+1)\frac{\vec{R}_s(\tilde{y}(t))}{2}, \qquad s = 1, 2. \tag{A.1}$$

where:

- Time t corresponds to one week,
- $\vec{\mathrm{N}}_{s,x}(t)$ is the vector corresponding to the abundance $\mathrm{N}_{s,x,l}(t)$ of prawns of species s of sex x ($x = ♀$ for female and ♂ for male) in size-class l alive at the start of time t.
- $\mathbf{X}_{s,x}$ is the size-transition matrix. It corresponds to the probability of an animal of species s and sex x in size-class i growing into size-class j during one time-step (i.e. week), and is assumed to be governed by a normal distribution as described in (Punt et al., 2010).
- $\mathbf{Suv}_s(t)$ is the diagonal survival matrix for the species s during the time t as:

$$\mathbf{Suv}_s(t) = \begin{bmatrix} \exp(-Z_{s,1}(t)) & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \exp(-Z_{s,L}(t)) \end{bmatrix}$$

  with $Z_{s,l}(t)$ the total mortality on animals of species s in size-class l during time t.

- $\alpha_s(t)$ is the fraction of the annual recruitment for the species s that occurs during the time t.
- $\vec{R}_s(\tilde{y}(t))$ is the vector of recruitment[10] of species s by size-class l during the 'biological' year $\tilde{y}(t)$:

$$R_{s,l}(\tilde{y}(t)) = \begin{cases} R_s(\tilde{y}(t)) & \text{if } l = 1, \\ 0 & \text{otherwise.} \end{cases} \tag{A.2}$$

  the size-class $l = 1$ corresponds to animals of 15 mm length. Equation (A.2) implies that recruitment contributes only to the first size-class in the model.

AppendixA.2. Recruitment estimation

The 'biological' year, $\tilde{y}(t)$, corresponding to time t is defined by:

$$\tilde{y}(t) = \begin{cases} y(t) & \text{for (t modulo 52)} < 40, \\ y(t) - 1 & \text{for (t modulo 52)} \geq 40. \end{cases} \tag{A.3}$$

where $y(t)$ stands for the year y corresponding to the time t.

Equation (A.3) implies that a 'biological' year $\tilde{y}(t)$ ranges from week 40 (roughly the start of October) of year $(y(t) - 1)$ to week 39 (roughly the end of September) of year $y(t)$. Recruitment involves complex biological and environmental processes that vary over time. Due to a large influence on recruitment events to the catch, it is important to take into account this variability. $R_s(\tilde{y}(t) + 1)$ stands for the recruits of species s in the fishery during a 'biological' year $(\tilde{y}(t) + 1)$ and is assumed to be related to the spawning stock size index $\mathrm{S}_s(y(t))$ of the year $y(t)$, according to a Ricker stock-recruitment relationship fitted assuming temporally correlated environmental variability and down-weighting recruitments, as in Punt et al. (2010, 2011), and given by:

$$R_s(\tilde{y}(t) + 1) = \alpha_s^{Rick} \mathrm{S}_s(y(t)) \exp\left(-\beta_s^{Rick} \mathrm{S}_s(y(t))\right) \exp\left(\eta_s(y(t) + 1)\right). \tag{A.4}$$

where α_s^{Rick} and β_s^{Rick} are the parameters of the Ricker stock-recruitment relationship for the species s and $\eta_s(y(t))$ represents the temporally correlated environmental variability term of the year $y(t)$ as:

$$\begin{cases} \eta_s(y(t)) = \rho_s \eta_s(y(t)) + \sqrt{1 - \rho_s^2} \xi_s(y(t)), \\ \xi_s(y(t)1) \leadsto \mathcal{N}(0, \sigma_s^2). \end{cases} \tag{A.5}$$

with ρ_s the environmentally driven temporal correlation in recruitment, and σ_s^2 is the environmental variability in recruitment.

AppendixA.3. Fishing mortality

Fishing mortalities of species $s = 1, 2, 3$ are given by:

$$\begin{cases} F_{s,l,f}(t) = \mathrm{A}_s(t)\mathrm{Sel}_{s,l} q_{s,f} \mathrm{E}_f(t), & s = 1, 2 \quad \text{and} \quad f = 1, 2 \\ F_{3,f}(t) = \mathrm{A}_s(t) q_{s,f} \mathrm{E}_f(t), & s = 3 \quad \text{and} \quad f = 1, 2. \end{cases} \tag{A.6}$$

where $\mathrm{A}_s(t)$ is the relative availability of animals of species s during time t and $\mathrm{E}_f(t)$ is fishing effort (days at sea) associated with grooved or brown tiger prawn sub-fishery $f = 1, 2$ at time t. Catchability $q_{s,f}$ corresponds to the fishing mortality of species s associated with one unit of fishing effort of fishing strategy f and is assumed constant over the simulation period. $\mathrm{Sel}_{s,l}$ is the selectivity of the fishing gear on animals of species s in size-class l (assumed to be a logistic function of length, identical for both strategies[11], and constrained so that selectivity is < 1 for sizes < l_∞ which is a von Bertalanffy growth curve parameter).

[10] the sex-ratio of the recruits is assumed to be 50:50 in the absence of data (Punt et al., 2011)

[11] This is assumed in the absence of catch length-frequency data by species and strategy.

AppendixA.4. CPUE

Annual average banana catch per unit effort (CPUE) are computed from white banana prawn annual biomass $B_{s=4}(y(t))$, as:

$$\mathrm{CPUE}_4(y(t)) = q_{4,3} B_3(y(t)), \tag{A.7}$$

where $q_{4,3}$ is the catchability of the white banana prawn ($s = 4$) by the banana prawn sub-fishery ($f = 3$). Estimated values of $q_{4,3}$ are given in appendix B table B.1.

Appendix B: Bio-economic parameter values

This appendix displays the values of the biological and economic parameters used to calibrate the bio-economic model presented in sections 2, AppendixA.1 and AppendixA.2. Table B.1 displays the parameters related to the white banana prawn. Tables B.2 and B.3 summarize respectively the annual stock dynamics and catchabilities parameter values for the grooved and brown tiger and blue endeavour prawns. Tables B.5 and B.6 summarize the values of parameters involved in the profit equation. Table B.7 exhibits the weekly proportion of tiger prawn sub-fishery effort directed towards grooved and brown tiger prawn fishing strategies used to split the tiger prawn sub-fishery effort into grooved and brown tiger prawn fishing strategies as described in section 2.5.

Table B.1: Estimated parameters related to white banana prawn ($s = 4$ and $f = 3$).

	B_s^- (in thousand tonnes)	B_s^+ (in thousand tonnes)	catchability, $q_{s,f}$
white banana prawn	28.72	125.8	0.0000142

Table B.2: Stock dynamic parameters by species s

	Values by species s		
Parameters	grooved tiger	brown tiger	blue endeavour
Natural mortality (week^{-1}). M_s	0.045	0.045	0.045
Ricker parameter. α_s^{Rick}	1182.51	1108.81	483.496
Ricker parameter. β_s^{Rick}	0.715945	0.581685	0.761467
Temporal correlation in recruitment. ρ_s	-0.379982	-0.322691	-0.339732
Variance in recruitment. σ_s^2	0.0682356	0.124784	0.0930268
Average mass (in kg/animal). $\tilde{\upsilon}_{s.sx}$			17.63 23.24

Table B.3: Estimated values of catchabilities $q_{s,f}$ by species s and by tiger prawn fishing strategies $f = 1, 2$ for a fishing power of the fishery as in 2010.

	Tiger prawn sub-fishery	
prawn species	grooved tiger prawn fishing strategy $f = 1$	brown tiger prawn fishing strategy $f = 2$
grooved tiger	0.0001219	0.0000152
brown tiger	0.0000111	0.0001219
blue endeavour	0.0001149	0.0002839

Table B.4: Weekly stock dynamic parameters by species s.

	Relative weekly recruitment, $\alpha_s(t)$			Relative weekly spawning, $\beta_s(t)$			Relative weekly availability, $A_s(t)$		
weeks	*P.s.*	*P.e.*	*M.e.*	*P.s.*	*P.e.*	*M.e.*	*P.s.*	*P.e.*	*M.e.*
1	0.0623	0.05	0.0217	0.0056	0.0065	0.0153	1	1	0.222
2	0.0724	0.0492	0.0234	0.0056	0.0065	0.0153	1	1	0.25
3	0.0753	0.046	0.0251	0.0056	0.0065	0.0153	1	1	0.278
4	0.0683	0.0395	0.0272	0.0056	0.0065	0.0153	1	1	0.285
5	0.0613	0.0331	0.0294	0.005	0.0067	0.0153	1	1	0.292
6	0.0544	0.0267	0.0315	0.0046	0.0068	0.0065	1	1	0.304
7	0.0475	0.0209	0.0336	0.0046	0.0068	0.0065	1	1	0.306
8	0.041	0.0191	0.0286	0.0046	0.0068	0.0065	1	1	0.333
9	0.0347	0.018	0.0212	0.0052	0.0129	0.0065	1	1	0.361
10	0.0283	0.0169	0.0187	0.0055	0.0175	0.0142	1	1	0.389
11	0.0225	0.016	0.0137	0.0055	0.0175	0.0142	1	1	0.417
12	0.0196	0.0166	0.0148	0.0055	0.0175	0.0142	1	1	0.406
13	0.0172	0.0173	0.0158	0.0058	0.018	0.0142	1	1	0.394
14	0.0148	0.0181	0.0168	0.0077	0.0213	0.0176	1	1	0.383
15	0.0124	0.0189	0.0179	0.0077	0.0213	0.0176	1	1	0.372
16	0.0106	0.0179	0.0189	0.0077	0.0213	0.0176	0.99	1	0.361
17	0.0093	0.0156	0.0177	0.0077	0.0213	0.0176	0.98	1	0.383
18	0.0079	0.0133	0.0165	0.0104	0.0294	0.0176	0.96	1	0.406
19	0.0066	0.011	0.0153	0.0108	0.0307	0.0214	0.95	1	0.428
20	0.0056	0.009	0.0141	0.0108	0.0307	0.0214	0.93	0.99	0.444
21	0.0053	0.0079	0.0148	0.0108	0.0307	0.0214	0.88	0.96	0.489
22	0.005	0.0068	0.0154	0.01	0.0255	0.0214	0.84	0.92	0.533
23	0.0047	0.0057	0.016	0.0088	0.0186	0.022	0.8	0.89	0.578
24	0.0045	0.0047	0.0166	0.0088	0.0186	0.022	0.75	0.85	0.622
25	0.0044	0.0047	0.0173	0.0088	0.0186	0.022	0.7	0.82	0.667
26	0.0044	0.005	0.0185	0.0104	0.0191	0.022	0.65	0.78	0.722
27	0.0044	0.0054	0.0198	0.0197	0.0218	0.026	0.59	0.74	0.778
28	0.0043	0.0057	0.021	0.0197	0.0218	0.026	0.53	0.7	0.833
29	0.0044	0.0056	0.0223	0.0197	0.0218	0.026	0.54	0.69	0.889
30	0.0046	0.0053	0.0236	0.0197	0.0218	0.026	0.59	0.72	0.917
31	0.0048	0.005	0.0249	0.0317	0.0301	0.026	0.64	0.74	0.944
32	0.0049	0.0047	0.0262	0.0365	0.0334	0.0305	0.69	0.77	0.972
33	0.0051	0.0044	0.0274	0.0365	0.0334	0.0305	0.74	0.79	1
34	0.0052	0.0042	0.0277	0.0365	0.0334	0.0305	0.8	0.82	0.994
35	0.0052	0.004	0.028	0.0369	0.0282	0.0305	0.86	0.84	0.989
36	0.0053	0.0038	0.0282	0.0379	0.0153	0.0287	0.92	0.87	0.983
37	0.0054	0.0036	0.0285	0.0379	0.0153	0.0287	0.98	0.89	0.978
38	0.0053	0.004	0.0288	0.0379	0.0153	0.0287	1	0.92	0.972
39	0.005	0.0047	0.0233	0.0379	0.0153	0.0287	1	0.94	0.939
40	0.0048	0.0054	0.0179	0.0491	0.0252	0.0199	1	0.96	0.906
41	0.0046	0.0061	0.0125	0.0491	0.0252	0.0199	1	0.99	0.872
42	0.0051	0.0098	0.007	0.0491	0.0252	0.0199	1	1	0.833
43	0.0065	0.0177	0.0072	0.0491	0.0252	0.0199	1	1	0.736
44	0.0078	0.0256	0.0074	0.0393	0.0212	0.0199	1	1	0.639
45	0.0092	0.0334	0.0076	0.032	0.0183	0.0185	1	1	0.542
46	0.0111	0.0406	0.0078	0.032	0.0183	0.0185	1	1	0.444

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weeks	$\alpha_s(t)$ P.s.	$\alpha_s(t)$ P.e.	$\alpha_s(t)$ M.e.	$\beta_s(t)$ P.s.	$\beta_s(t)$ P.e.	$\beta_s(t)$ M.e.	$A_s(t)$ P.s.	$A_s(t)$ P.e.	$A_s(t)$ M.e.
47	0.0159	0.0438	0.0094	0.032	0.0183	0.0185	1	1	0.394
48	0.0212	0.0464	0.0111	0.0261	0.017	0.0185	1	1	0.344
49	0.0265	0.0489	0.0128	0.0112	0.014	0.0097	1	1	0.294
50	0.0319	0.0514	0.0145	0.0112	0.014	0.0097	1	1	0.244
51	0.0405	0.0517	0.0161	0.0112	0.014	0.0097	1	1	0.194
52	0.0507	0.0509	0.0184	0.0112	0.014	0.0097	1	1	0.208

Table B.5: Prawn prices $p_s(2010)$ (AU$ per kilogramme) by species group and size-class in 2010.

Species group	All sizes	<40 mm	40-45 mm	45-50 mm	50-55 mm	>55 mm
Tiger, $p_{tig,l}$	19.05	15.30	19.91	20.83	27.19	26.83
Endeavour, $p_{s=3}$	9.64					
Banana, $p_{s=4}$	9.5					

Table B.6: Economic parameters.

(a) Variable costs	sub-fishery	
Parameters	tiger ($f = 1, 2$)	banana ($f = 3$)
Unit Cost of repairs and maintenance, c_f^K	332 (AU$/day)	529 (AU$/day)
Base unit cost of fuel and grease, $c_f^F(2010)$	1815 (AU$/day)	2236 (AU$/day)
Share cost of labor, c^L	0.24	0.24
Cost of packaging and gear maintenance, c^M	0.92 (AU$/kg)	0.92 (AU$/kg)
(b) Fixed costs and rates		
Parameters	Value	
Annual vessel costs, W_v	296,847 (AU$/vessel)	
Opportunity cost of capital, r	0.05	
Economic depreciation rate, d	0.037	
Average value of capital, ψ_v	1,135,693 (AU$/vessel)	
(c) NPF fishery status in 2010		
Variable	Value	
Number of vessels, K(2010)	52	
Annual average effort (days/vessel), $e(2010)$	162	

Table B.7: Pattern of weekly effort by tiger prawn fishing strategy (i.e. grooved or brown) set to 0 for closed weeks (predicted for the year 2010).

weeks	Tiger prawn fishing strategies effort pattern: proportion directed to grooved tiger prawn, $\Upsilon^{strat}(t)$	proportion directed to brown tiger prawn, $(1 - \Upsilon^{strat}(t))$
1	0	0
2	0	0
3	0	0

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weeks	proportion of effort towards grooved tiger prawn, $\Upsilon^{strat}(t)$	proportion of effort towards brown tiger prawn, $(1 - \Upsilon^{strat}(t))$
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0.55052002	0.44947998
15	0.44202646	0.55797354
16	0.54208048	0.45791952
17	0.37494679	0.62505321
18	0.48131314	0.51868686
19	0.47449422	0.52550578
20	0.50102323	0.49897677
21	0.4236849	0.5763151
22	0.46343995	0.53656005
23	0.46358818	0.53641182
24	0	0
25	0	0
26	0	0
27	0	0
28	0	0
29	0	0
30	0	0
31	0.14321391	0.85678609
32	0.17552077	0.82447923
33	0.21198361	0.78801639
34	0.29388628	0.70611372
35	0.45558605	0.54441395
36	0.57216275	0.42783725
37	0.67915149	0.32084851
38	0.73330751	0.26669249
39	0.77412768	0.22587232
40	0.7814252	0.2185748
41	0.82888647	0.17111353
42	0.80903904	0.19096096
43	0.82492339	0.17507661
44	0.83268046	0.16731954
45	0.83485189	0.16514811
46	0.80818265	0.19181735
47	0.79468166	0.20531834
48	0.72204043	0.27795957
49	0	0
50	0	0
51	0	0

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weeks	proportion of effort towards grooved tiger prawn, $\Upsilon^{strat}(t)$	proportion of effort towards brown tiger prawn, $(1 - \Upsilon^{strat}(t))$
52	0	0

Appendix C: Statistical analyses

This appendix displays the outputs of statistical analyses used to calibrate the bio-economic model and scenario projections. Figure C.1 represents the linear regression used for the projection of the fuel prices and figure C.2 the one used in the effort allocation model described in section 2.5

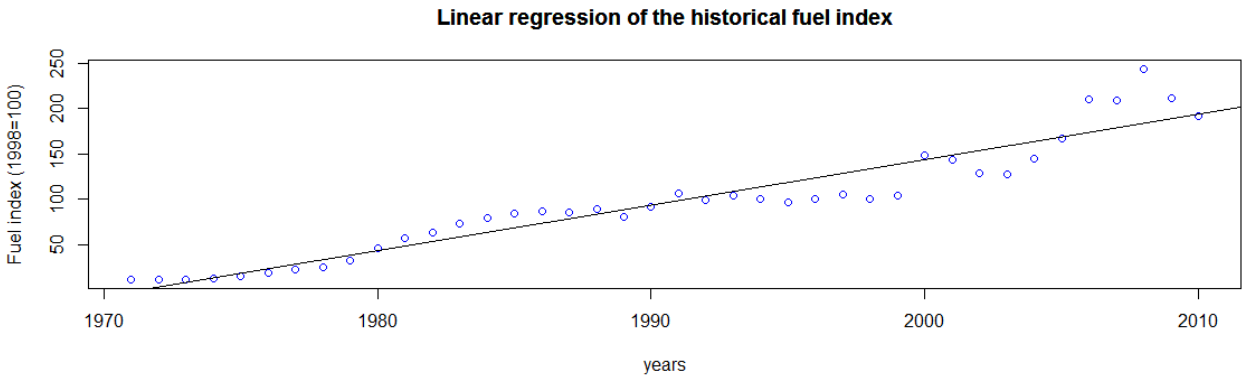


Figure C.1: Linear regression of fuel price index relying on historical data from 1971 to 2010. $R^2 = 0.9033$ and Pvalue= $2.2 * 10^{-16}$ (<0.05, significant). The slope of the regression line is 4.9831 (meaning an increase of 5% per year). Data source: ABARES (2010).

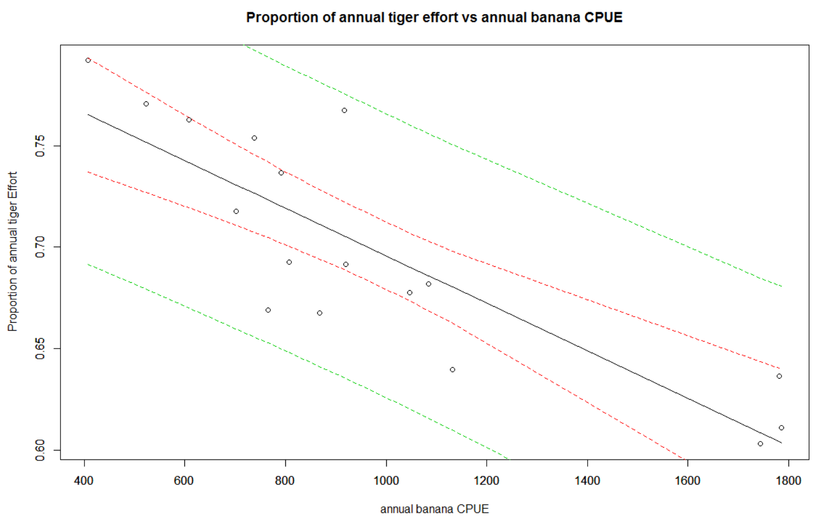


Figure C.2: Linear regression ($\propto_{1+2}(y) = a\text{CPUE}_{s=4}(y) + b$) between the average annual banana catch per unit effort, $\text{CPUE}_{s=4}$ and the annual proportion of tiger prawn sub-fishery effort, $\propto_{1+2}$. Model relies on historical catches and effort data from 1994 to 2010. $R^2 = 0.7016$ and Pvalue= $1.657 * 10^{-5}$ (<0.05, significant). $a = -1.172 * 10^{-4}$ and $b = 0.813$.

Appendix D: Algorithm of weekly tiger effort allocation.

This appendix is a complement of the step 2 of effort allocation model described in section 2.5. Figure D.3 described the algorithm used to allocate the annual effort of the tiger prawn sub-fishery to weeks according to the annual proportion of tiger effort associated.

The probability distribution on which depend the random selection of a year between 1994 et 2010 is such as the probability of selecting a historical year y_H is inversely proportional to the normalised value of the difference between the annual proportion of tiger prawn effort of year $y(t)$ and the annual proportion of tiger prawn effort of the year y_H. The historical weekly pattern of tiger prawn sub-fishery effort corresponding to the historical year y_H is then used to allocate the annual tiger prawn sub-fishery effort of the year $y(t)$ to weeks.

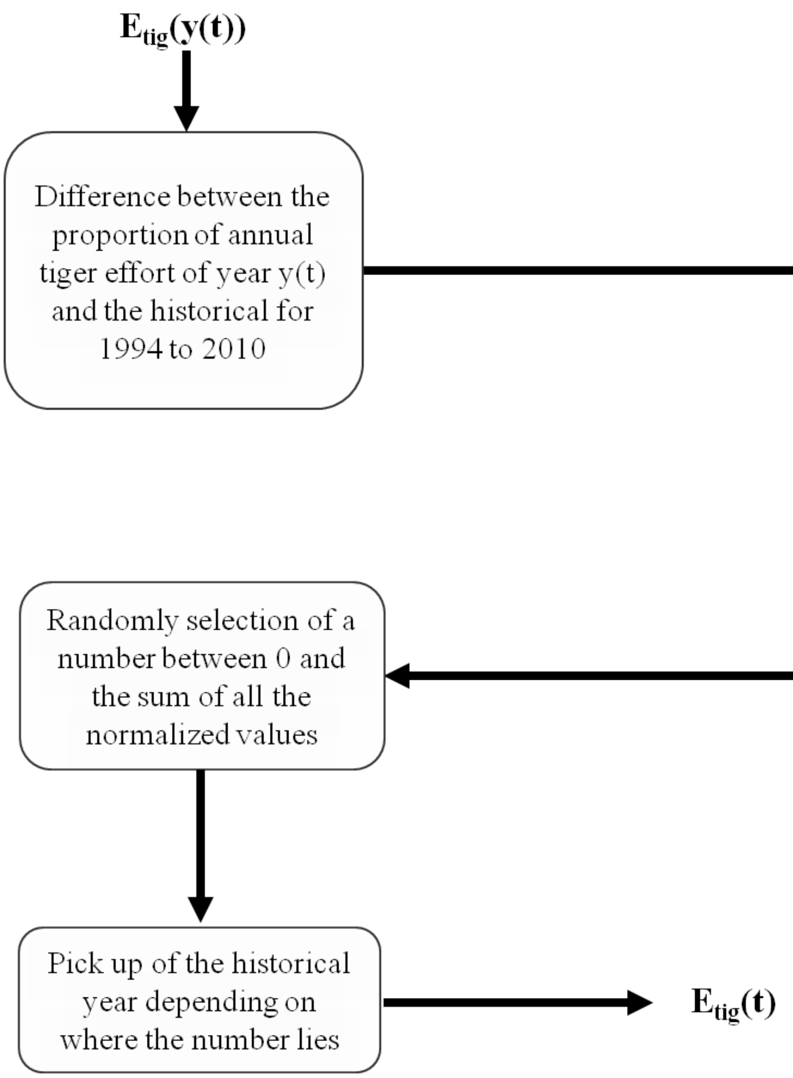


Figure D.3: Flowchart of the algorithm used to determined the tiger prawn sub-fishery weekly effort pattern for the year $y(t)$.

Appendix E: To go further: Mean-variance analyses of S

Biological performance of the fishery is studied through the spawning stock size indices for grooved and brown tiger and blue endeavour prawns.

To study the trade-offs between the mean biological performance of the fishery and the variance of this performance under different economic assumptions and fishing management options, mean-variance analyses are setting up. Figures E.4 shows the mean-variance analyses of the biological indicators, i.e. spawning stock size indices, of the NPF with seven effort allocation strategies and four fishing capacity strategies[12].

AppendixE.1. Performance of various effort allocation strategies

Results focusing on the SQ fishing capacity strategy outputs (blue dots in figure E.4) show that the banana specialisation effort allocation strategies (T_0, T_{10} and T_{20}) resulting in a decrease in fishing pressure on species targeted by the tiger prawn sub-fishery, leads to the highest mean spawning stock size indices for each of the three species (figures 4(a) to 4(c)). This effect increases with the degree of banana prawn specialisation. Tiger prawn specialisation effort allocation strategies (T_{90} and T_{100}) have strong effects on the three species, greater tiger prawn specialisation entailing decreases in mean spawning stock size indices. Moreover, biological variability for grooved tiger prawn and blue endeavour prawn increases with the degree of banana prawn specialisation, while for brown tiger prawn it increases with the degree of tiger prawn specialisation.

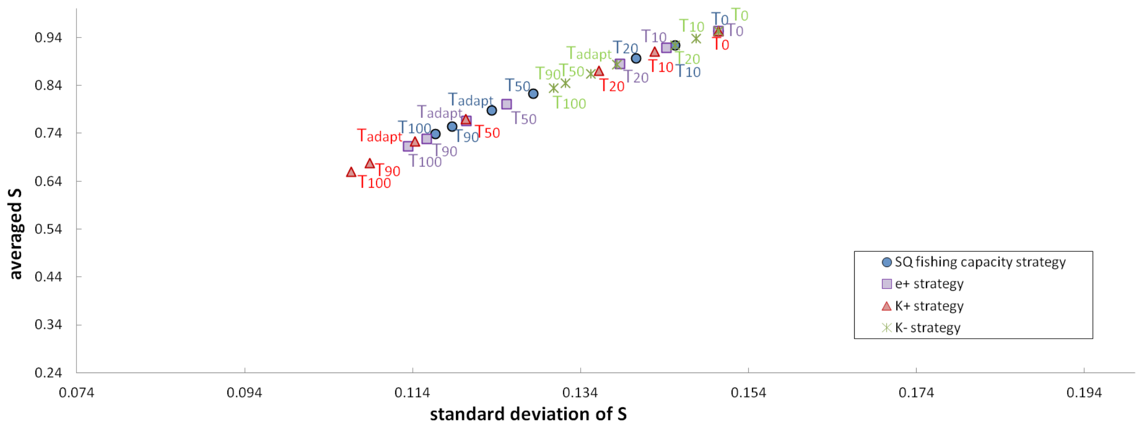
AppendixE.2. Performance of various fishing capacity strategies

Comparison of biological performance across the four fishing capacity strategies (figures E.4 and 4(c)) shows that higher levels of fishing capacity decreases the spawning stock sizes indices. Biological variability of grooved tiger prawn and blue endeavour prawn also decreases when fishing capacity increases. However, variability of the brown tiger prawn slightly increases with fishing pressure (i.e. with increases in fishing capacity and tiger prawn specialisation strategies).

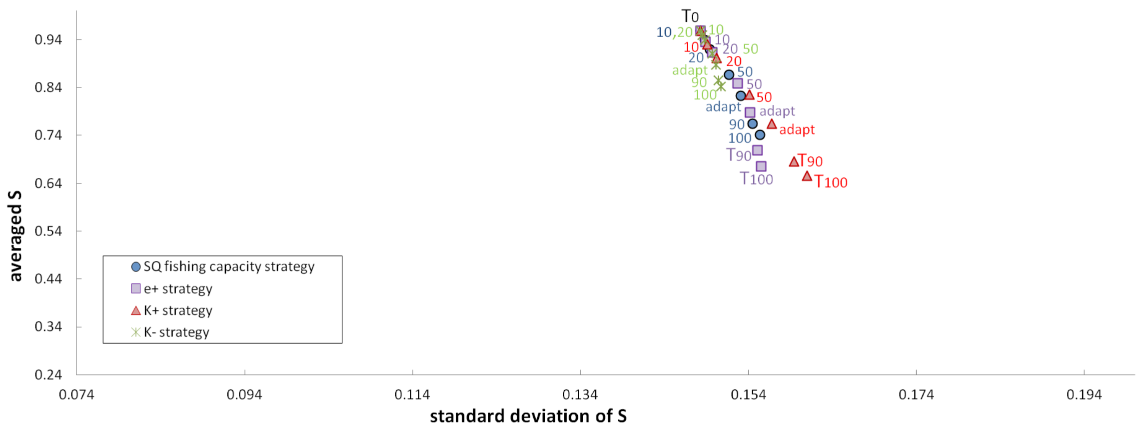
AppendixE.3. Discussion around mean-variance analyses of S

Analyses of alternative effort allocation strategies with various fishing capacity strategies shows that tiger prawn specialisation strategies have strong negative impact on mean spawning stock levels,

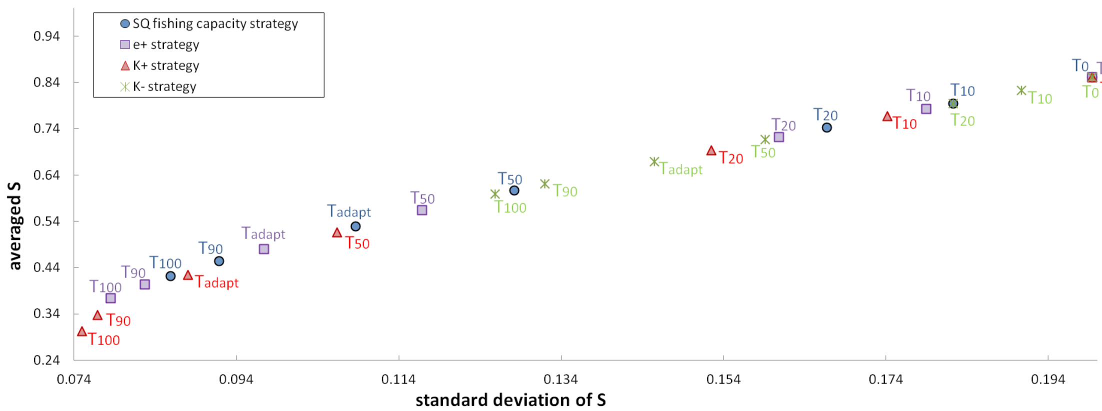
[12]Outputs under both base case and most likely economic scenarios are similar.



(a) Grooved tiger prawn, s = 1



(b) Brown tiger prawn, s = 2



(c) Blue endeavour prawn, s = 3

Figure E.4: Biological mean-variance analysis of grooved tiger prawn in (a), brown tiger prawn in (b) and blue endeavour prawn in (c). Each dot represents the mean annual spawning stock size index $S_s(y(t))$ of species s versus the standard deviation associated. Results are presented by effort allocation strategy (T_{adapt}, T_0, T_{10}, T_{20}, T_{50}, T_{90} and T_{100}) under different capacity strategies. The blue circles correspond to a status quo (SQ), the purple cross to an increase in effort per vessel (e^+), the red triangles to an increase in the number of vessels (K^+) and the green square to a decrease in the number of vessels (K^-) fishing capacity strategy.

while impacts on tiger and endeavour prawn species are reduced with banana prawn specialisation strategies.

Moreover, the biological variability determining economic risk in the fishery may arise from two different causes. On one hand, variability for grooved tiger and blue endeavour prawns increases with the degree of banana specialisation and the decrease in fishing capacity. This can be explained by the fact that with decreasing fishing pressure, and increases in stock biomasses, fluctuations due to stock-recruitment relationships become stronger. On the other hand, biological variability for brown tiger prawn slightly increases with fishing pressure (i.e. with the degree of tiger specialisation and level of fishing capacity). Brown tiger prawn is the species characterized by a decline in its spawning stock size over the projection. Therefore, above a certain level of fishing mortality, increases in fishing pressure tend to increase stock variability. This is because at small stock sizes, stock biomass may become strongly dependent on recruitment only. It could be a way to assess if a species is in danger of overexploitation or not. Stocks with small spawning stock sizes combined with high variability could be considered as not sustainably exploited.