Modelling the cost of sustainability in the Australian Northern Prawn Fishery

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Abstract

Fisheries management must address multiple, often conflicting objectives in a highly uncertain context. In particular, while the bio-economic performance of trawl fisheries is subject to high levels of biological and economic uncertainty, the impact of trawling on broader biodiversity is also a major concern for management. The purpose of this study is to analyse the trade-offs associated with balancing biological, ecological and economic objectives within the Australian Northern Prawn Fishery (NPF). The NPF is one of the most valuable federally managed commercial fisheries and derives its revenue from different prawn species with different dynamics and recruitment processes. A stochastic co-viability approach is proposed to assess the ability of the fishery to remain within a set of biological, ecological and economic constraints throughout simulation time. Results show that, due to the variability that characterizes the interactions of the fishery with the ecosystem, management strategies which approximate the current fishing strategies cannot be considered, in our study, as viable, due to the fact that the ecological constraint cannot be met. Based on the model results, strategies that would achieve high co-viability probabilities involve reducing the fleet size; but only at the cost of reducing the economic yield compared to strategies maximizing the net present value of the entire fishery.

Keywords: Bio-economic modelling, co-viability analyses, cost of sustainability, uncertainty,

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Northern Prawn Fishery.

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1. Introduction

Marine fisheries management is characterised by multiple, often conflicting objectives (Crutchfield, 1973, Charles, 1989), underpinned by ecological, economic and social viewpoints. There is growing evidence that fishing activities cause physical damage to habitats and affect not only the exploited stocks, but also populations of non-targeted species (Hall and Mainprize, 2005) this is due to the use of poorly selective gears which induce catches of non-targeted fishes (i.e. by-catch and by-product) or unwanted length grades of the targeted species. Most by-catch species are discarded and returned to the water with high mortality rate (Alverson et al., 1994). Discards represent a significant proportion of global marine catches and are generally considered to constitute waste, and indicate suboptimal use of fishery resources (Kelleher, 2005). As a result, second only to the sustainability of the stocks themselves, the management and mitigation of by-catch is one of the most pressing issues facing the commercial fishing industry worldwide (Hall and Mainprize, 2005). In the case of demersal trawling, such as prawn trawling, fishing activities can be particularly damaging to non-targeted species and habitats. Trawl nets used to catch prawns have small mesh and are towed along a biologically-diverse seabed. This results in large quantities of discarded by-catch, including impacts on endangered or vulnerable and often charismatic species, including turtles, sharks, rays, sea snakes, sawfish and seahorses. Alverson et al. (1994) estimated that around one-third of the world's discards are associated with prawn trawl fishing and Kelleher (2005) estimated that on average 62.3% of total prawn trawl catch in weight is discarded.

As stressed by Cheung and Sumaila (2008), understanding the trade-offs between ecological, economic and social objectives is important in designing policies to manage ecosystems and fisheries. However, few fisheries jurisdictions have adopted harvest control rules which explicitly account for multiple biological, ecological, economic, social and political objectives.

In this context, viability modelling has been presented by several authors (Bene et al., 2001, Cury et al., 2005, Eisenack et al., 2006, Doyen et al., 2012, Péreau et al., 2012) as a potentially relevant bio- economic modelling framework. Viability theory, introduced mathematically by Aubin (1990), aims at identifying decision rules such that a set of constraints, representing various objectives, is respected at any time. It can be useful in a multi-criteria context as this approach identifies a domain of possibilities, and trade-offs between potentially conflicting objectives or constraints (Baumgärtner and Quaas, 2009). It has also been recognized that sustainable use of fish resources over time should account the inherent risk and uncertainty of fishery systems (Garcia, 1996, Hilborn and Peterman, 1996). By combining biological, economic and ecological goals from stochastic simulation models, the stochastic co-viability approach (Baumgärtner and Quaas, 2009, De Lara and Martinet, 2009, Doyen and De Lara, 2010), can be used to address important issues of vulnerability, risk, safety and precaution, and to determine the ability of a particular resource system to achieve specified sustainability objectives. However, the potential cost of such sustainability objectives can be questioned.

The objective of the present paper is to use the framework of viability analysis including biological, economic and biodiversity conservation management objectives to estimate the cost of balancing conflicting objectives in the management of a mixed fishery. This is done by (i) applying a stochastic co-viability (CVA) framework of analysis as proposed in Doyen et al. (2012) and Gourguet et al. (2013) to a simplified bio-economic model of the Australian Northern Prawn Fishery (NPF); (ii) including in the CVA assessment a formal way of representing biodiversity conservation constraints; (iii) identifying viable fleet capacities related to various combinations of effort between the different sub-components of the fishery; and (iv) estimating the cost of sustainability of such viable management strategies.

2. Material and Methods

2.1. The Australian Northern Prawn Fishery

The Northern Prawn Fishery (NPF), located off Australia's northern coast and established in the late 1960s, is a multi-species trawl fishery which harvests several high-value prawn species, each with different dynamics and levels of biological variability. The fishery derives its revenue from an unpredictable naturally fluctuating resource, the white banana prawn (*Penaeus merguiensis*), and a more predictable resource comprising two tiger prawns species (grooved tiger prawn, *Penaeus semisulcatus* and brown tiger prawn, *Penaeus esculentus*). These three species account for 95% of the total annual landed catch value of the fishery (ABARES, 2010). The fishery 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 consists of two sub-fisheries that are (to a large degree) spatially and temporally separate. The 'banana prawn sub-fishery' is 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 (Woodhams et al., 2011). The banana prawn sub-fishery operates mostly during the first season. The fleet then switches during the second season to the tiger prawn sub-fishery, for which catches per unit effort are lower than for white banana prawns, but less variable. However, if banana prawns are still available in large enough numbers, some vessels will continue to target them. Two different fishing strategies can also be identified within the tiger prawn sub-fishery, one associated with catching grooved tiger prawns (hereafter called the 'grooved tiger prawn fishing strategy') and the other associated with catching brown tiger prawns (hereafter called the 'brown tiger prawn fishing strategy'). Both tiger prawn fishing strategies result in by-catch of tiger and endeavour prawn species. Moreover, environmental issues within the NPF involve high proportions of by-catch, interactions with protected species and potential impact of trawling on benthic communities (Woodhams et al., 2011). By-catch in the NPF consist of small fish, invertebrates, sponges, other megabenthos, rays, sawfish, sharks, sea snakes and turtles (Stobutzki et al., 2001). Many of these species are dead when discarded, or have a low survival rate (Hill and Wassenberg, 2000).

Management of the NPF is aimed at achieving maximum economic yield (MEY), which reflects both stock conservation and economic performance objectives. However, demonstrating ecological sustainability is also a legislative requirement for an increasing number of fisheries worldwide, particularly demersal trawl fisheries such as the NPF (Griffiths et al., 2006). Therefore, the Australian Fisheries Management Act 1991 and the Environment Protection and Biodiversity Conservation Act 1999 require that negative effects on endangered species are avoided, catches of non-targeted species are reduced to a minimum, and the long-term sustainability of by-catch and by-product populations is demonstrated. The certification for sustainable fishing practices by the Marine Stewardship Council[1] (MSC) in November 2012 acknowledged the efforts undertaken by the NPF to limit its impacts on ecosystem.

2.2. Bio-economic model

This study is based on a bio-economic model, presented in Gourguet (2013) and Gourguet et al. (2014), which allows for the explicit modelling of the banana and tiger prawn sub-fisheries.

2.2.1. Biological dynamics of prawns

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 mortality. White banana prawns are repre-

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[1] The MSC is an international non-profit organisation set up to promote solutions to the problem of overfishing.

sented without explicit density-dependence mechanisms, due to highly variable recruitment and absence of a defined stock-recruitment relationship.

- Tiger and endeavour prawns: multi-species, stochastic and dynamic models.

  The bio-economic model includes explicit population dynamics of grooved ($s = 1$) and brown ($s = 2$) tiger prawns and blue endeavour ($s = 3$) prawns (see Gourguet et al. (2014), for further detail). Annual recruits in the fishery for species $s = 1, 2, 3$ are assumed to be related to the spawning stock size index of species s for the previous year, according to a Ricker stock-recruitment relationship fitted assuming temporally correlated environmental variability and down-weighting recruitments, as described in Punt et al. (2010) and Punt et al. (2011).

  The annual spawning stock size indices $\mathrm{S}_s(y(t))$ of the grooved and brown tiger and blue endeavour prawns ($s = 1, 2, 3$) for the year $y(t)$ are calculated as in (Punt et al., 2010) and are described in equation 1 .

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

  where $\mathrm{N}_{s,♀,l}(t)$ is the abundance of prawns of species s of sex $x = ♀$ (for female) in size-class l alive at the start of time t which corresponds to one time step (i.e. one week), $y(t)$ is the year corresponding to the time t[2], $\beta_s(t)$ measures the relative amount of spawning of species s during the time t, and $\gamma_{s,l}$ corresponds to the proportion of females of species s in size-class l that are mature. $Z_{s,l}(t)$ is the total mortality on animals of species s in size-class l during time t and is defined by:

$$Z_{s,l}(t) = M_s + F_{s,l}(t). \tag{2}$$

  with M_s the natural mortality of animals of species s and $F_{s,l}(t)$ the fishing mortality of animals of species s and size-class l at time t. Details on fishing mortality are given in

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[2] Year $y(t)$ is a function of week t, where weeks are numbered 1,. . . , 52, 53,. . . , 102, 103, . . .

Gourguet et al. (2014).

- 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. It is assumed that spawning stock biomasses of white banana prawns do not influence significantly the stock abundances the following years and that annual environmental influences are independent. Therefore, in the present study, white banana prawn annual biomass is modelled as a uniform i.i.d. random variable:

  $$B_s(y(t)) \rightsquigarrow \mathcal{U}(B_s^-, B_s^+), \qquad s = 4. \tag{3}$$

  with $B_{s=4}(y(t))$ the stochastic biomass of white banana prawn for the year $y(t)$, and $B_{s=4}^-$ and $B_{s=4}^+$ the uniform law bounds (the values are given in table B.1 in AppendixB).

2.2.2. *Harvesting and economics*

Catches are estimated by fishing strategy f (with f=1 and 2 for the grooved and brown tiger prawn fishing strategies, respectively; and $f = 3$ for the banana prawn sub-fishery). Weekly catches $Y_{s,l,f}(t)$ of species $s = 1, 2, 3$ in length-class l by tiger prawn fishing strategy ($f = 1, 2$); and annual catches $Y_{s=4,f=3}(y(t))$ of white banana prawns ($s = 4$) by the banana prawn sub-fishery ($f = 3$) for the year $y(t)$ are defined by the system of equations (4):

$$\begin{cases} Y_{s,l,f}(t) = \displaystyle\sum_x \upsilon_{s,x,l} \mathrm{N}_{s,x,l}(t) F_{s,l,f}(t) \frac{1 - \exp\left(-M_s - \sum_{f=1,2} F_{s,l,f}(t)\right)}{M_s + \sum_{f=1,2} F_{s,l,f}(t)} & s = 1, 2, 3 \quad \text{and} \quad f = 1, 2 \\ Y_{s,f}(y(t)) = q_{s,f} B_s(y(t)) \mathrm{E}_f^{\mathrm{y}}(y(t)) & s = 4 \quad \text{and} \quad f = 3. \end{cases} \tag{4}$$

with $\upsilon_{s,x,l}$ the mass of an animal of species $s = 1, 2, 3$ and sex x in size-class l, and $\mathrm{E}_f^{\mathrm{y}}(y(t))$ the annual effort of fleet f during year $y(t)$.

The economic component of the model estimates the flow of costs and revenues from fishing over time. Total annual profit of the whole fishery $\pi(y(t))$ for year $y(t)$ is expressed by:

$$\pi(y(t)) = \sum_{f=1}^{3} \sum_{t=52\left(y(t)-1\right)+1}^{52y(t)} \left(\mathrm{Inc}_f(t, \mathrm{E}_f(t)) - C_f^{var}\mathrm{E}_f(t)\right) - C_v^{fix}\mathrm{K}(y(t)). \tag{5}$$

where $\mathrm{Inc}_f(t, \mathrm{E}_f(t))$ is the annual gross income of fishing strategy f for the time t and related to $\mathrm{E}_f(t)$ the fishing effort (expressed in days at sea) of the fishing strategy f during time t. Annual gross incomes are described further in AppendixA. C_f^{var} corresponds to the variable cost for one unit of fishing effort of fishing strategy f, and C_v^{fix} is the annual fixed cost by vessel. Details on costs are given in Punt et al. (2010) and Gourguet et al. (2014). $\mathrm{K}(y(t))$ 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 and is given by:

$$\mathrm{NPV} = \sum_{y(t)=0}^{T} \frac{\pi(y(t))}{(1+\mathrm{r})^{y(t)}}. \tag{6}$$

where r is the discount rate (set to 5%), and T is the terminal year of the simulation.

Further details on the estimations of the bio-economic model parameters are given in Gourguet (2013) and Gourguet et al. (2014). Sub-indices used in this study are summarized in table 1 where their symbols, values and descriptions are displayed.

Table 1: Symbols, values and descriptions of the sub-indices used in the study.

Symbols	values	Description
s	1	grooved tiger prawn species
	2	brown tiger prawn species
	3	blue endeavour prawn species
	4	white banana prawn species
l	1 to 41	1-mm length-class between 15 to 55 mm
f	1	tiger prawn fishing strategy targeting the grooved tiger prawns
	2	tiger prawn fishing strategy targeting the brown tiger prawns
	1+2	tiger prawn sub-fishery which comprises the two tiger fishing strategies
	3	banana prawn sub-fishery which targets white banana prawns

2.2.3. *Sea snakes: impacted species*

Assessing the performance of the NPF also requires that its impacts on marine biodiversity be considered. NPF operations interact with several groups of threatened, endangered and protected (TEP) species including sea snakes, turtles, elasmobranchs (as sawfishes, sharks and ray), syngnathids (seahorses and pipe fishes) (AFMA, 2012). Reported interactions with sea snakes are generally an order of magnitude higher than reported interactions with other species (e.g., 4.1 sea snake interactions per day versus 0.056 turtle, 0.021 syngnathid and 0.6 sawfish interactions per day as reported by scientific observers during the tiger prawn season in 2010; c.f. Barwick, 2011). The amount of by-catch species caught in prawn trawl nets has been significantly reduced since 2000 through the mandatory introduction of Turtle Excluder Devices (TEDs) and By-catch Reduction Devices (BRDs). Nets with TEDs are particularly effective at reducing catches of larger animals such as turtles (by 99%), large rays and sharks (by 94% and 86%, respectively); in contrast, BRDs are more effective at excluding small fishes (Brewer et al., 2006). However, Brewer et al. (2006) estimate that nets with a combination of a TED and BRD reduced the catches of sea snakes (*Hydrophiidae*) by only 5%. Sea snake catches appear to be significantly correlated to fishing effort in the fishery, making them an interesting proxy to assess impacts of the fishery on the broader biodiversity.

Although the tiger and banana prawn sub-fisheries both use gear that can be broadly classified as demersal otter trawls, the method of gear deployment varies[3] The amount of by-catch thus varies by sub-fishery, making it important to consider their effects separately. Linear regressions, between historical sea snake catches $\mathrm{Y}_{\mathrm{snake},f}(y(t))$ by sub-fishery f(with $f = 1 + 2$ corresponding to the tiger prawn sub-fishery and $f = 3$ to the banana prawn sub-fishery) and the associated annual fishing effort $\mathrm{E}_f(y(t))$ by sub-fishery, are displayed in AppendixC (figure

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[3] In the tiger prawn sub-fishery, the trawl is generally lowered over suitable prawn habitat to fish as close as possible to the seabed, and is towed for three to four hours. In contrast, in the banana prawn sub-fishery the trawl gear is deployed for less than an hour on a prawn aggregation (or ‘boil’) in the water column identified using an echo sounder (Griffiths et al., 2007).

C.1). Table 2 displays the statistics of these regressions.

Table 2: Statistics of the linear regression between annual sea snake catches by tiger and banana prawn sub-fisheries and associated annual effort (intercept at 0).

	sub-fishery	
	tiger ($f = 1 + 2$)	banana ($f = 3$)
Adjusted R Square	0.785	0.778
Residual Variance σ_f^2	938.98	274.25
P-value	$8.843.10^{-6}$	$2.687.\ 10^{-5}$
Coefficient values a_f^{reg}	1.1883	0.5235

Estimation of total annual sea snake catches $\mathrm{Y}_{\mathrm{snake},f}(y(t))$ from tiger and banana prawn sub-fisheries are thus calculated separately as:

$$\begin{cases} \mathrm{Y}_{\mathrm{snake},1+2}(y(t)) = a_{1+2}^{reg}\mathrm{E}_{1+2}(y(t)) + \xi_{1+2}(y(t)), \\ \mathrm{Y}_{\mathrm{snake},3}(y(t)) = a_{3}^{reg}\mathrm{E}_{3}(y(t)) + \xi_{3}(y(t)). \end{cases} \tag{7}$$

with

$$\begin{cases} \xi_{1+2}(y(t)) \rightsquigarrow \mathcal{N}(0, \sigma_{1+2}^2), \\ \xi_3(y(t)) \rightsquigarrow \mathcal{N}(0, \sigma_3^2). \end{cases} \tag{8}$$

where $\mathrm{E}_{1+2}(y(t))$ and $\mathrm{E}_3(y(t))$ are respectively the annual effort of tiger and banana prawn sub-fisheries during the year $y(t)$. a_{1+2}^{reg} and a_3^{reg} are the coefficient values from the linear regressions by sub-fishery $f = 1 + 2, 3$ given in table 2. $\xi_{1+2}(y(t))$ and $\xi_3(y(t))$ are the residual terms for the year $y(t)$ and are assumed to be independent normally distributed random variables with mean equal to zero and variance σ_{1+2} and σ_3, respectively.

2.3. *Effort combinations*

The biological, economic and biodiversity performances of the fishery are examined under four[4] effort combinations. The effort combinations differ in terms of proportion of total annual effort allocated to the tiger prawn sub-fishery ($f = 1 + 2$) and are summarized in table 3. The

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[4] more intermediate combinations were studied and analysed, however, for the sake of simplicity, only four are displayed in this paper.

annual proportion $\propto_{1+2}(y(t))$ of effort directed towards the tiger prawn sub-fishery is expressed as in equation 9:

$$\begin{cases} \mathrm{E}^{y}(y(t)) = \mathrm{E}^{y}_{f=1+2}(y(t)) + \mathrm{E}^{y}_{f=3}(y(t)), \\ \propto_{1+2}(y(t)) = \dfrac{\mathrm{E}^{y}_{f=1+2}(y(t))}{\mathrm{E}^{y}(y(t))} \end{cases} \tag{9}$$

where $\mathrm{E}^{y}(y(t))$ is the total annual fishing effort for the entire NPF, $\mathrm{E}^{y}_{f=1+2}(y(t))$ corresponds to the annual effort of tiger prawn sub-fishery, and $\mathrm{E}^{y}_{f=3}(y(t))$ of banana prawn sub-fishery, during the year $y(t)$.

In three of the effort combinations, the annual proportion of total effort allocated to tiger prawns $\propto_{1+2}(y(t))$ is pre-defined. One 'banana effort combination' (T_{10}) consists of setting the annual proportion of tiger prawn effort $\propto_{1+2}$ to 10% of total annual effort. One 'tiger effort combination' (T_{90}) involves allocating 90% of the annual effort to the tiger prawn sub-fishery. A 'balanced' effort combination (T_{50}) is also analysed, in which total annual effort is split equally between the two sub-fisheries. Finally, an 'adaptive' effort combination ($\mathrm{T}_{\mathrm{adapt}}$), which reflects the current fishing behaviour in the NPF, is studied. Under this combination, the allocation of the total annual fishing effort between tiger and banana prawn fishing depends directly on white banana prawn catch per unit effort $\mathrm{CPUE}_{s=4}$ as described in Gourguet et al. (2014). The resulting proportion of total annual effort directed to the tiger prawns ranges between 60 and 76%.

Table 3: Effort combinations (in each row) considered in this study. The combinations differ in the annual effort $\mathrm{E}_{1+2}(y(t))$ allocated to tiger prawn sub-fishery.

Effort combinations	Description	Tiger prawn sub-fishery annual effort
T_{10}	$\propto_{1+2} = 10\%$.	$\mathrm{E}_{1+2}(y(t)) = 0.1\mathrm{E}(y(t))$
T_{50}	$\propto_{1+2} = 50\%$.	$\mathrm{E}_{1+2}(y(t)) = 0.5\mathrm{E}(y(t))$
$\mathrm{T}_{\mathrm{adapt}}$	see Gourguet et al. (2014).	$0.6\mathrm{E}(y(t)) < \mathrm{E}_{1+2}(y(t)) < 0.76\mathrm{E}(y(t))$
T_{90}	$\propto_{1+2} = 90\%$.	$\mathrm{E}_{1+2}(y(t)) = 0.9\mathrm{E}(y(t))$

For each of the four effort combinations, the annual tiger prawn effort is then allocated by week and between grooved and brown fishing strategies as described in Gourguet et al. (2014).

2.4. Stochastic co-viability analysis

A stochastic co-viability framework is used to assess the viability of the fishery system and to describe the trade-offs between biological, economic and biodiversity conservation management objectives under various fishing settings. The method requires specifying constraints on the values of indicators associated with biological, economic and biodiversity conservation objectives. Given the stochastic nature of the model (i.e. uncertainties in tiger and blue endeavour prawn recruitments, white banana prawn annual biomasses and annual sea snake catches), the performance of the fishery is assessed in terms of the probability of these constraints being met by the fishery at any point in time (Doyen and De Lara, 2010). The co-viability of the system is examined by simultaneously assessing the ability of the fishery to respect biological, economic and biodiversity conservation constraints at any time of the simulation and with sufficiently high probability.

In this study, the biological objective consists in ensuring the conservation of the prawn population by requiring that the spawning stock size index $\mathrm{S}_s(y(t))$ of each individual species $s = 1, 2, 3$ is maintained above a threshold value as:

$$\mathrm{S}_s(y(t)) \geq \mathrm{S}_s^{\mathrm{lim}}, \qquad s = 1, 2, 3. \tag{10}$$

with $\mathrm{S}^{\mathrm{lim}}$ the limit spawning stock size index of species s defined as the minimal historically observed spawning stock size index values over the 1970-2010 period (values in table B.2 in AppendixB).

In our study, the NPF fishing settings are defined by two variables: the annual number of vessels[5] K and the annual proportion of effort $\propto_{1+2}$ directed towards the tiger prawn sub-fishery. The biological viability probability (PVA) of the system according to K and $\propto_{1+2}$ is

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[5] The total annual effort $\mathrm{E}^{\mathrm{y}}(y(t))$ for the entire NPF can be expressed as in equation (11):

$$\mathrm{E}^{\mathrm{y}}(y(t)) = e\mathrm{K}(y(t)). \tag{11}$$

where e is the annual average effort per vessel (set to the value estimated for 2010: 162 days at sea) and $\mathrm{K}(y(t))$ the number of vessels for year $y(t)$.

then assessed by:

$$\mathrm{PVA}\Big(\mathrm{K}, \propto_{1+2}\Big) = \mathbb{P}\Big(\text{constraints (10) are satisfied for } y(t) = y_0, \ldots, T\Big). \tag{12}$$

The economic objective in this study requires maintaining a minimum total annual profit for the NPF.

$$\pi(y(t)) \geq \pi^{\mathsf{min}} \tag{13}$$

with π^{min} the minimal profit set to 60% of the annual profit in 2010 (values in table B.2 in AppendixB).

The economic viability probability of the fishery (EVA) is expressed as:

$$\mathrm{EVA}\Big(\mathrm{K}, \propto_{1+2}\Big) = \mathbb{P}\Big(\text{constraint (13) are satisfied for } y(t) = y_0, \ldots, T\Big). \tag{14}$$

A biodiversity conservation objective is also considered in this study, and viability on this domain requires maintaining the catch of sea snakes below a maximum 'allowed' level:

$$\mathrm{Y}_{\mathrm{snake}}(y(t)) \leq \mathrm{Y}_{\mathrm{snake}}(2010) \tag{15}$$

with $\mathrm{Y}_{\mathrm{snake}}(2010)$ the maximum allowed sea snake catch set to the value observed in 2010 (values in table B.2 in AppendixB).

The ecological or impact viability probability (IVA) of the NPF is then described by:

$$\mathrm{IVA}\Big(\mathrm{K}, \propto_{1+2}\Big) = \mathbb{P}\Big(\text{constraint (15) are satisfied for } y(t) = y_0, \ldots, T\Big). \tag{16}$$

Co-viability analysis requires that biological, economic and biodiversity constraints are jointly considered. These constraints characterize an acceptable sub-region of the phase space within which the fishery evolves. A particular trajectory followed by the fishery will be called viable if it remains in this region during the prescribed period of time, with a sufficiently high probability (e.g. 90%). Thus, the bio-eco-diversity performance of the system is evaluated by the probability of co-viability (CVA) of the system in a stochastic context and given by:

$$\mathrm{CVA}\Big(\mathrm{K}, \propto_{1+2}\Big) = \mathbb{P}\Big(\text{constraints (10), (13) and (15) are satisfied for } y(t) = y_0, \ldots, T\Big). \tag{17}$$

2.5. *Management strategies*

For the four effort combinations described in section 2.3, we compare different management strategies which differ in their management objectives and rely on different number of vessels involved in the fishery.

1000 trajectories of spawning stock size indices and annual total profits are simulated over a 10 year period from 2010. Furthermore, to account for the uncertainty in the estimation of sea snake catches, for each of these 1000 trajectories, 10 estimations of sea snake catches are made as described in equation (7). Each trajectory represents a possible state of nature for each year of the simulation, $\omega(.) = (\omega_1(.),\omega_2(.), \omega_3(.),\omega_4(.)\ ,\omega_5^i(.)_{i=1:10})$; which stands for the set of annual recruitments of tiger (grooved and brown) and blue endeavour prawn as detailed in Punt et al. (2010, 2011), of white banana prawn annual biomasses as in equation (3), and of total annual sea snake catches as in equation (7). The different $\omega_i(.)$ are assumed to be independent by species. Each combination of effort combination and management strategies is simulated with the same set of $\omega(.)$.

A status quo management strategy SQ is analysed and consists of setting the number of vessels to the current level, which corresponds to K^{SQ}=52 vessels. A CVA management strategy is defined such that it guarantees the conservation of tiger and blue endeavour prawn stocks, maintains of the economic viability of the whole fishery and reduces the impacts of trawling on the broader biodiversity. The number of vessels $\mathrm{K}^{\mathrm{CVA}}$ are thus identified such as to maximize the co-viability probability of the system:

$$\mathrm{CVA}\Big(\mathrm{K}^{\mathrm{CVA}}\Big) = \max_{\mathrm{K}} \mathrm{CVA}\Big(\mathrm{K}\Big). \tag{18}$$

A conventional economic management strategy NPV is also examined, where the number of vessel $\mathrm{K}^{\mathrm{NPV}}$ is identified such as to maximize the average[6] net present values (NPV) of the

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[6] among the thousand trajectories

whole fishery:

$$\mathrm{NPV}\Big(\mathrm{K}^{\mathrm{NPV}}\Big) = \max_{\mathrm{K}} \mathbb{E}_{\omega(.)} \Big[\mathrm{NPV}\Big(\mathrm{K}\Big)\Big]. \tag{19}$$

The numerical implementations and computations of the model have been carried out with the scientific software SCILAB[7].

3. Results

The biological, economic, ecological, and co-viability probabilities (PVA, EVA, IVA and CVA), and the overall economic performance of the whole fishery (i.e. tiger and banana prawn sub-fisheries), represented by the mean net present value (NPV) of the fishery, are analysed taking into account the stochastic nature of the model, for the four effort combinations under the three management strategies described in sections 2.3 and 2.5, respectively.

3.1. Optimal fleet sizes

The optimal number of vessels according to CVA and NPV management strategies and effort combinations are displayed in figure 1.

Figure 1 shows that the greater is the annual proportion of tiger prawn sub-fishery effort, smaller is the optimal fleet size for both management strategies. Furthermore, the numbers of vessels to maximize NPV are higher that the one to maximize the CVA. We can note that the difference between the two management strategies, in terms of number of vessels, decreases when the proportion of tiger prawn sub-fishery effort increases.

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

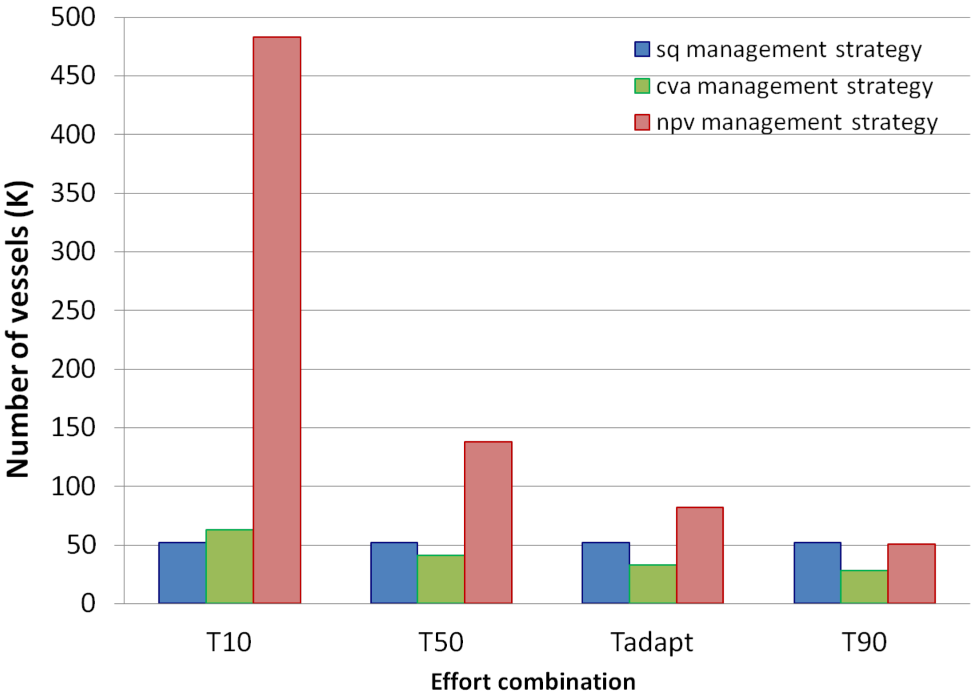


Figure 1: Optimal fleet sizes according to management strategies and sorted by effort combinations (x axis).

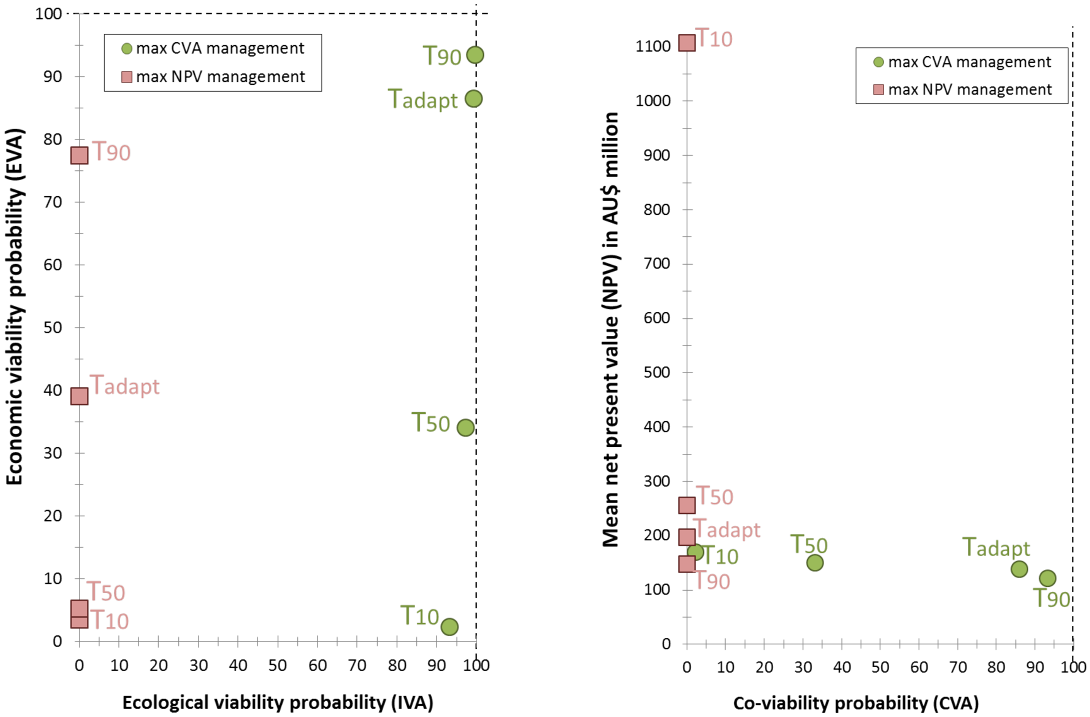
3.2. *Management strategy performances*

The values of the biological, economic, ecological and co- viability probabilities, and the associated mean NPV, for each effort combination (T_{10}, T_{50}, T_{adapt} and T_{90}) and management strategies (sq, cva and npv), are given in table 4. Co-viability probabilities are used here as indicators of the sustainable performance of the fishery.

Table 4: Biological, economic, ecological and co-viability probabilities of four effort combinations with three management strategies.

Management strategies	Effort combination	K	Viability probabilities PVA	EVA	IVA	CVA	mean NPV (in AU$ million)
SQ	T_{10}	52	100	1.6	**99.8**	1.6	140.35
	T_{50}	52	100	35.8	31.81	11.79	175.89
	T_{adapt}	52	100	79	0.44	0.38	177.02
	T_{90}	52	100	75	0	0	146.84
CVA	T_{10}	63	100	2.4	93.23	2.26	169.27
	T_{50}	41	100	34.1	97.36	33.15	149.83
	T_{adapt}	33	100	86.5	99.32	85.95	138.49
	T_{90}	28	100	**93.5**	99.68	**93.18**	122.16
NPV	T_{10}	483	100	3.5	0	0	**1107.63**
	T_{50}	138	99.7	5.3	0	0	255.50
	T_{adapt}	82	100	39.1	0	0	197.05
	T_{90}	51	100	77.5	0	0	146.95

Table 4 shows that the biological constraints will be met in the fishery with a very high degree of certainty under all management strategy combinations. However, the economic and ecological constraints are met with widely varying probabilities. Results suggest that, under the modelling assumptions used, the current management of the fishery (i.e. T_{adapt} effort combination with 52 vessels) may not be viable, with its co-viability probability (CVA) equal to 0.38%. This means that less than 1% of the simulated trajectories remain within the biological, economic and biodiversity conservation constraints at all simulation times. More specifically this management strategy has a moderate economic risk with an economic viability probability (EVA) equal to 79%, while a very low ecological viability: $\text{IVA}(K^{sq}, T_{adapt}) = 0.44\%$. Concerning the other management strategies, the highest CVA would be obtained with a T_{90} effort combination and a reduction of the fleet size to 28 vessels: $\mathrm{CVA}(28, \mathrm{T}_{90}) = 93.18\%$. As to the highest mean NPV, it would be obtained with a T_{10} effort combination and an increase of the fleet to 483 vessels. However, the minimal annual profit required by the economic objective would be guaranteed for all simulation times in only 3.5% of the trajectories. This demonstrates the strong economic variability associated with this fishing settings, and especially the great risk of having annual profit inferior to the economic threshold set in this study. Furthermore, this strategy would not be ecologically viable, with zero probability of not exceeding the allowed level of sea snake catch for all years of the simulation.



(a) EVA versus IVA

(b) NPV versus CVA

Figure 2: Economic viability probability (EVA) versus ecological viability probability (IVA) in (a) and mean net present value (NPV) versus co-viability probability (CVA) in (b) of *maxNPV* and CVA management strategies with the four effort combinations (written near the associated dot).

Figure 2(a) displays the economic versus the ecological viability performances of the four effort combinations under CVA and NPV management strategies. This figure shows that for management strategies involving a reduced number of vessels (i.e. CVA management strategies), there is globally a greater than 95% probability of not violating the IVA constraint. Moreover, there exists win-win management strategies involving high ecological and economic viability probabilities (T_{adapt} and T_{90} effort combinations under management strategy aiming at maximizing the CVA).

Figure 2(b) exhibits a strong trade-off between mean economic performance (through mean NPV) and the bio-eco-diversity performance (or co-viability probability, CVA) of the fishery. On one hand, while the best mean economic performance is achieved with T_{10} effort combination under a NPV management strategy (related to an increase of the fleet size), this management settings are not viable, as defined in this study. On the other hand, the effort combinations T_{adapt} and T_{90} under CVA management strategies (associated with a decrease of the fleet size) are the best performing in terms of viability probabilities. However, there is an economic loss of increasing their CVA, when compared to strategies maximizing the economic yield. This economic loss can be interpreted as a 'cost of sustainability' associated with the objective to meet all the constraints imposed on the fishery, i.e. the opportunity cost of increasing CVA. This cost can be estimated by effort combination from the difference between the mean NPV value of the NPV management strategy and that with the CVA management strategy.

Table 5: Cost of sustainability in terms of value and in terms of percentage of the highest NPV (by effort combination) and potential maximum increase of CVA for the four effort combinations.

Effort combinations	cost of sustainability		gain of CVA in %
	value in AU$ million	% of the highest NPV in %	
T_{10}	938.36	84.72	2.26
T_{50}	105.57	41.36	33.25
T_{adapt}	58.56	29.72	85.95
T_{90}	24.71	16.87	93.18

Table 5 displays the costs of sustainability for each effort combination, the equivalent of these costs in terms of percentage of maximum economic yield that is achievable and the gain of CVA associated. We can note that the cost of sustainability (in terms of value and percentage of highest achievable NPV) is decreasing and the associated gain of CVA is increasing when the proportion of total annual effort allocated to the tiger prawn sub-fishery increases.

3.3. Marginal cost of sustainability

It has been demonstrated that, when we are considering the range of number of vessels between K^{NPV} and K^{CVA}, the CVA is increasing when the fleet size decreases. To explore the changes in the total cost of sustainability when the fleet size is gradually reduced, we explore in this section the marginal costs of removing one vessel from the fishery. Figure 3 displays, for T_{50}, T_{adapt} and T_{90} effort combinations[8], the marginal costs of removing one vessel and the associated increase of CVA (i.e. marginal gain of CVA) in function of the number of vessels reduced from the optimal number of vessel that maximizes economic yield (K^{NPV}) to the number of vessel that maximizes CVA (K^{CVA}) [9].

Figure 3 shows that for each effort combination, the marginal cost of removing one vessel is increasing when the fleet size is decreasing. Moreover, it appears that there exists a certain number of vessel where the marginal gain of CVA of removing one vessel is reaching a peak. We can also note that the highest marginal gain of CVA is reached with a tiger specialization effort combination (T_{90}). Furthermore, while T_{50} and T_{adapt} have highest total cost of sustainability compared to that with T_{90}, the highest marginal cost is estimated with T_{90}. The total cost of sustainability of T_{50} and T_{adapt} are higher because they need to remove a greater number of vessels, therefore the cumulative marginal costs are higher for these effort combinations than for the T_{90} one.

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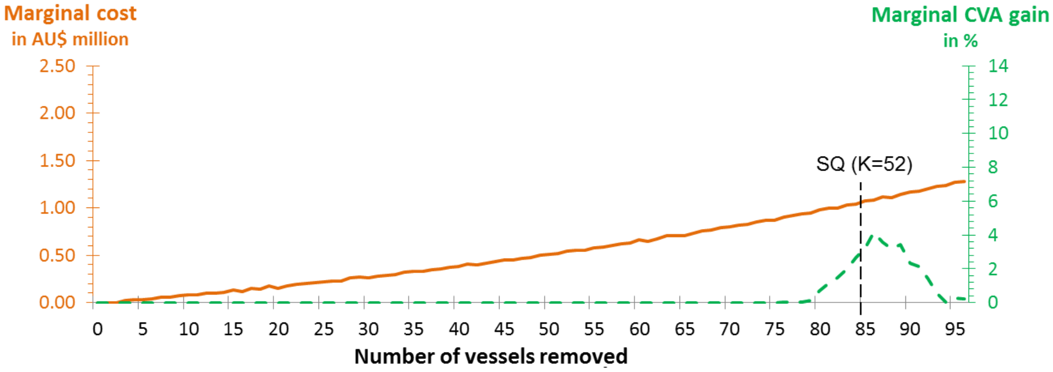
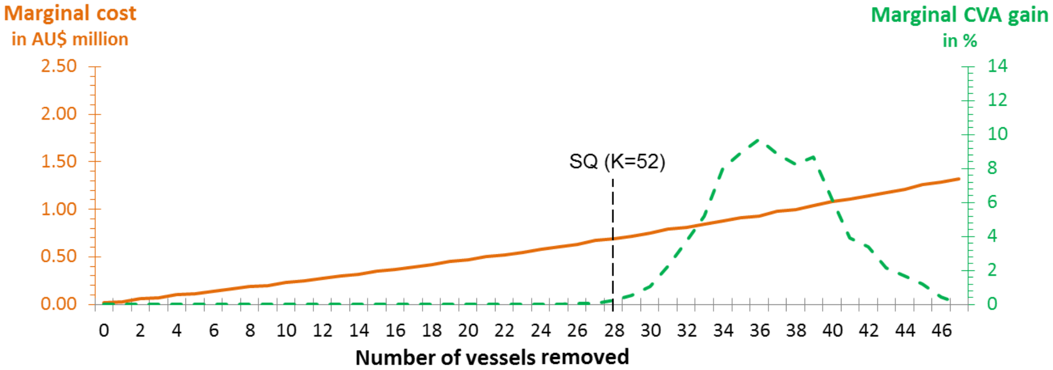
[8] As for the T_{10} effort combination, its gain of CVA is only 2.26% for a great cost, we decided then to not study its marginal cost of sustainability.

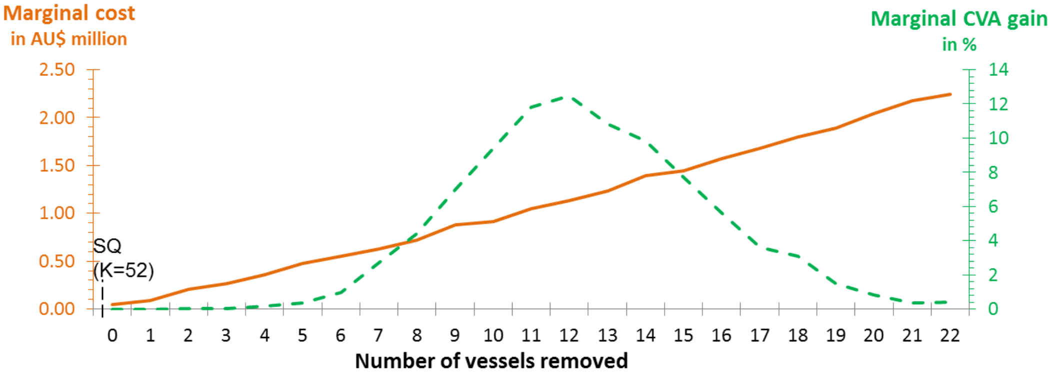
[9] Marginal costs (ΔC) is calculated as:ΔC(nb of vessels removed= $K^{NPV} - x$) = NPV(K = x)−NPV(K = $x+1$). And marginal gain of CVA (ΔCVA) is calculated as: ΔCVA(nb of vessels removed= $K^{NPV} - x$) =| CVA(K = x) − CVA(K = $x + 1$) | .



(a) T_{50} effort combination



(b) T_{adapt} effort combination



(c) T_{90} effort combination

Figure 3: Marginal cost and marginal gain of CVA when the number of vessel is decreasing from the optimal number of vessel that maximizes economic yield (K^{NPV}) to the number of vessel that maximizes CVA (K^{CVA}); with T_{50} effort combination (with K in x-axis from $K^{NPV,T_{50}} = 138$ to $K^{CVA,T_{50}} = 33$) in (a), T_{adapt} effort combination (with K in x-axis from $K^{NPV,T_{adapt}} = 82$ to $K^{CVA,T_{adapt}} = 33$) in (b), and T_{90} effort combination (with K in x-axis from $K^{NPV,T_{90}} = 51$ to $K^{CVA,T_{90}} = 28$) in (c).

4. Discussion

The modelling approach proposed here accounts for the interactions between tiger and banana prawn sub-fisheries within a simplified model of the Northern Prawn Fishery (NPF), and allows assessing various management strategies. Co-viability probabilities are used as indicators of the sustainable performance of the fishery under uncertainty, taking into account the objectives of maintaining high levels of annual profit, preserving target stocks, and limiting the impacts of the fishery on marine biodiversity. The study compares, for different effort combinations (relying on the proportion of effort allocated to the tiger prawn sub-fishery) under various management strategies (depending on the number of vessels), the co-viability probability (CVA) and a more classical economic performance measure, the average net present value (NPV) of the fishery. The results illustrate the inevitable trade-offs which exist in managing mixed fisheries. Achieving certain constraints may entail a cost in terms of lost economic returns. This is what we propose to call the ‘cost of sustainability’.

4.1. Assessment of the viability of the fishery

Based on our simulations, and regarding the assessed prawn species taken into account in this study and the associated biological thresholds, it appears that the biological constraints have relatively less influence on the viability probability, as compared to the economic and biodiversity conservation constraints. Indeed the population viability probability (PVA) reaches 100% in almost all cases, which means that the biological objective is achieved at any time of the simulation and for any simulated state of nature (i.e. uncertainties on biological recruitment of grooved and brown tiger and blue endeavour prawns).

Based on the data used to calibrate the model and modelling assumptions (particularly, assumptions on stock-recruitment relationships, effort allocation model, sea snake catch estimations, and on prices and costs), it appears that the status quo management approach may not be viable when assessed against the economic and biodiversity constraints[10] defined in this analysis.

The analysis reveals that management strategies aiming at maximizing CVA with a current adaptive effort combination ($\mathrm{T}_{\mathrm{adapt}}$, where the proportion of effort directed towards tiger prawn sub-fishery is comprised between 60 and 76%) or a 'tiger specialization' effort combination allocating 90% of the annual effort towards tiger prawn sub-fishery (T_{90}) allow compromises between management objectives leading to high co-viability probabilities. Simulation results show that improving the viability status of the fishery would involve a reduction in the number of vessels (which is currently set to 52 from MEY objective analyses).

4.2. *Cost of sustainability*

A trade-off in fishery management performance based on mean NPV and co-viability criteria was observed for the NPF. In one hand, management strategies leading to the highest NPV were indeed related to strongly reduced economic viability and zero ecological viability probabilities. The decrease in economic viability under a NPV management strategy (which maximizes the NPV) reflects increased inter-annual variability and violation of the inter-annual-equity objective. On the other hand, analyses presented in this paper highlighted that higher co-viability probabilities can be achieved (with CVA management strategies), but only at the cost of reducing the economic yield compared to a strategy maximizing the NPV. This economic loss can be interpreted as a 'cost of sustainability' associated with the objective to meet all the constraints imposed on the fisheries; i.e. the opportunity cost, in terms of reduced NPV, of increasing the co-viability probabilities. This cost can be estimated from the difference be-

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[10] It is not surprising that the status quo management approach may not be ecologically viable, as defined in this study. The threshold for biodiversity conservation constraint is indeed set to the 2010 sea snake catch and residual terms randomly distributed are integrated in sea snake catch estimations. Therefore sea snake catch estimations with a status quo management approach will be above and below the 2010 sea snakes catch (the biodiversity conservation threshold to not exceed), and ecological viability probability is calculated regarding the respect of constraint for all time. This means that if the sea snake catches among one given trajectory are superior to this threshold for at least one year of the simulation, the trajectory will be considered as not ecologically viable. This reflects a willing to guarantee that 2010 sea snake catch is not exceeded for any state of nature.

tween the mean NPV value obtained with the NPV management strategy and that with the CVA management strategy. Based on the assumptions defined here, it appears that, with the current effort combination T_{adapt}, increasing the probability of respecting all constraints considered in this study may have a potential cost of sustainability of AU$ 58.56 million (or 29.72% of the NPV value which would be obtained when maximizing the NPV) over 10 years.

In the case of the NPF, if the fishing industry strives for strong total economic performance regardless of inter-annual equity, increasing the fleet capacity to 438 vessels and allocating only 10% of the annual effort towards the tiger prawn sub-fishery would appear to be in order. The gain in terms of NPV compared to the expected NPV value estimated with the current management settings would be AU$ 930.61 million (i.e. 525% of the NPV estimated with current management settings). However, it would be associated with an economic viability probability of 3.5%, which means that for only 3.5% of the trajectories, the annual profit is guaranteed at all time to be superior to the economic threshold set in this study. However, if the fishing industry is seeking the highest possible co-viability probability (i.e. reducing at a minimum biological, economic and biodiversity conservation risks), the management options that perform best in our analysis involve a fleet capacity reduced to 28 vessels associated with an allocation of 90% of the total annual effort towards the tiger prawn sub-fishery. The 'cost of sustainability' in this situation would be equal to 16.87% of the highest NPV achievable with this effort combination.

An interesting point to note is that the marginal cost of removing one vessel from the fleet is increasing when the fleet size is decreasing. Furthermore the marginal cost of reducing the fleet size from the current 52 vessels would be higher for the first removed vessels when a greater part of the annual effort is directed towards the banana prawn sub-fishery. This reflects the fact that a bigger fleet is more fit for banana specialization effort combinations, while smaller fleets are more advantageous for tiger specialization effort combinations. Compromises can therefore be made according the willing of the fishing industry to reduce its economic risk and impacts on broader biodiversity, but consequently reducing its potential economic yield.

4.3. CVA as a step towards integrated management of mixed fisheries

The consideration of the multi-dimensional nature of marine fisheries management appears as an unavoidable reality. As part of this, consideration of the environmental impacts of fishing activities is a crucial concern, as these impacts can lead to changes in biodiversity and ultimately change the overall functionality of the ecosystem (Pauly et al., 1998, Dulvy et al., 2000). However, fishery scientists and managers often do not have the information required to properly assess fishery impacts on non-targeted species and communities, or to develop management measures to ensure the fishery operates in an ecologically sustainable manner (Zhou and Griffiths, 2008). In such cases, use of biodiversity indicators as proposed in this study can assist in explicitly addressing the impacts of fishing on biodiversity in assessments. The stochastic co-viability approach proposed here offers formal recognition of the multi-objective nature of management for the NPF, and means to integrate this with the current understanding of the dynamics of a mixed non-selective fishery system. The model illustrates the benefits of formally combining integrated bio-economic modelling with the multi-criteria evaluation underlying the co-viability framework analysis. This study demonstrates the value of the stochastic co-viability approach by providing a ‘sustainability metric’ through co-viability probabilities allowing to rank strategies and therefore help stakeholders to choose the appropriate fishing management settings according to their contextual management objectives. This approach allows for identification of a range of possibilities, according to various external sources of pressure on management, notably environmental ‘pressures’ from environmental lobbies and government policies. The co-viability probabilities can therefore bring a consensus in fisheries management as it does not favour any of the objectives over another. As such, management decisions may be more likely to be accepted by the various stakeholders.

4.4. Perspectives

The viability approach has been proposed by several authors (e.g. Mullon et al., 2004, Cury et al., 2005, Chapel et al., 2008), as a well-suited modelling framework for Ecosystem-Based Fishery Management (EBFM). EBFM must manage targeted species in the context of the overall state of the system, habitat, protected species, and non-targeted species. This study is a first step in this direction for the NPF. However, extensions of the biodiversity indicator could be considered to assess the differences in impacts from tiger and banana prawn sub-fisheries. Following the study of Bustamante et al. (2010), impacts from tiger and banana prawn sub-fisheries could be assessed more accurately with the integration of benthos species in our model. Aggregation of these species in two groups, as sessile and mobile benthos, can be relevant to take into account the contrasted impacts of tiger and banana prawn sub-fisheries on the ecosystem. For instance, tiger prawn sub-fishery have greater impacts on sessile benthos than banana prawn sub-fishery. Moreover, prawns and some mobile benthos species being predators of certain sessile benthos species, competition relationships exist between prawns and some mobile benthos species. The integration of such trophic interactions (prey-predator and indirect competition) can thus also reinforce this study. The work presented in Bustamante et al. (2010), which employs a trophic mass-balance model (using Ecopath with Ecosim software) to explore the ecological effects of demersal trawling in the NPF, could be adapted for our study.

Several other expansions of this modelling could also be considered like the modelling of dynamic control variables through a dynamic annual number of vessels. A more social objective could also be added to the study through a social constraint, for instance via a minimal production of prawns to guarantee.

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Appendix A: Gross income details

Gross income $\mathrm{Inc}_f(y(t))$ for grooved ($f = 1$) and brown ($f = 2$) tiger prawn fishing strategies are calculated from catches $Y_{s,l,f}(t)$ of tiger and blue endeavour prawns ($s = 1, 2, 3$) and gross income $\mathrm{Inc}_3(y(t))$ for banana prawn sub-fishery ($f = 3$) from catches $Y_{4,3}(y(t)$ of white banana prawn ($s = 4$), as described by equation (A.1).

$$\begin{cases} \mathrm{Inc}_f(y(t)) = \displaystyle\sum_{t=52\big(y(t)-1\big)+1}^{52y(t)} \left(\sum_{s=1}^{3}\sum_{l} p_{s,l} Y_{s,l,f}(t)\right), & s = 1, 2, 3 \quad \text{and} \quad f = 1, 2. \\ \mathrm{Inc}_f(y(t)) = p_s Y_{s,f}(y(t)), & s = 4 \quad \text{and} \quad f = 3. \end{cases} \tag{A.1}$$

where $p_{s,l}$ is the average market price per kilogram for animals of species $s = 1, 2, 3$ in size-class l (related to five market categories for the tiger prawns and corresponding to an average price for the blue endeavour prawns, as they are represented through an aggregated length-class). Grooved and brown tiger prawns are marketed together as ‘tiger prawns’ under a common size-dependent price, therefore $p_{s,l}$ are identical for $s = 1$ and $s = 2$. The average price per kilogram of white banana prawns is denoted $p_{s=3,4}$.

Appendix B: Bio-economic parameter values

This appendix displays the estimated values for the white banana prawn dynamics and the values of the biological, economic and ecological parameters used in the definition of the constraints described in section 2.4.

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

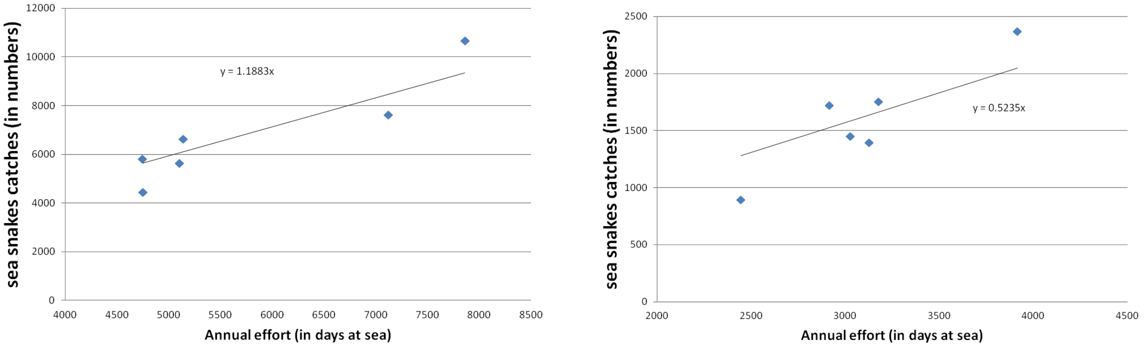
	B_s^- (in thousand tonnes)	B_s^+ (in thousand tonnes)	catchability, $q_{s,f}$
white banana prawn	28.72	125.8	0.0000142

Table B.2: Threshold used in co-viability approach.

Threshold		Value
Biological S_s^{lim}	grooved tiger prawn, $s = 1$	0.293539
	brown tiger prawn, $s = 2$	0.234883
	blue endeavour prawn, $s = 3$	0.128637
Economic, π^{min}	Profit of reference, $0.6\pi(2010)$	7,140,000 (AU$)
Ecological, $Y_{\text{snake}}(2010)$	Sea snake catch estimated in 2010	8430

Appendix C: Statistics

This appendix displays the linear regressions between historical sea snake catches $Y_{\text{snake},f}(y(t))$ by sub-fishery $f = 1 + 2, 3$ and the associated annual fishing effort $E_f(y(t))$ of the prawn sub-fishery $f = 1 + 2, 3$ in figure C.1.



(a) Tiger prawn sub-fishery

(b) Banana prawn sub-fishery

Figure C.1: Linear regression between historical annual sea snake catches by sub-fishery and annual effort associated. Regression for the tiger prawn sub-fishery is represented in (a) and banana prawn sub-fishery in (b).