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Effectiveness of harvest strategies in achieving multiple management objectives in a multispecies fishery*

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Fisheries management is characterised by multiple objectives, some of which may be complementary, while others may require trade-offs between outcomes. Balancing these objectives is made more complex in the case of multispecies and multigear fisheries. In this paper, we develop a bioeconomic model that captures the key elements of such a fishery to test a range of potential harvest strategies to provide insights into how economic target reference points could lead to both desirable and undesirable management outcomes (e.g. discards). The model is developed as a long-run optimisation model to identify target reference points to achieve multispecies maximum economic yield, and a dynamic recursive optimisation model, which includes more realistic representation of fishers' behaviour, such as discards and trading of under-caught species quotas. The potential economic, social and ecological impacts are evaluated using data envelopment analysis (DEA). The results suggest that the use of proxy target reference points can result in short-term economic benefits at the cost of slower stock recovery and higher discarding. Limiting the number of species subject to quota controls may also prove beneficial in multispecies fisheries, while ensuring quota markets are efficient is likely to produce benefits irrespective of the harvest strategy adopted.

Key words: bioeconomic model, harvest strategy, multispecies maximum economic yield, proxy target reference points, Southern and Eastern Scalefish and Shark Fishery.

1. Introduction

The potential ecological and economic benefits that fisheries can generate if managed effectively have been long established (Gordon 1954; Scott 1955). While these potential benefits can be substantial (Arnason *et al*. 2009), how these benefits can be achieved is less well established. The implementation of

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harvest strategies and harvest control rules (i.e. pre-agreed decision rules that are triggered and adhered to given a series of limit and target reference points) is increasingly being applied to fisheries worldwide (e.g. Walters 1975; Vasconcellos 2003; Smith *et al.* 2008; Dowling *et al.* 2014; Kvamsdal *et al.* 2016; Quetglas *et al.* 2017), and combined with efficiency-incentivising rights-based management instruments are in combination expected to move fisheries towards improved economic and ecological objectives (Beddington *et al.* 2007).

More recently, the need to consider governance and social objectives alongside ecological and economic objectives in fisheries management has gained greater recognition (Stephenson *et al.* 2017). While enhancing tradeable use rights (such as through individual transferable quotas (ITQs)) has been found to improve profitability in many fisheries (Dupont *et al.* 2005; Fox *et al.* 2006; Thébaud *et al.* 2014), several studies have questioned the social implications of such measures (McCay 1995; Olson 2011; McCay 2016). For example, rights-based measures have been actively resisted by groups opposed to the ‘privatisation’ of public resources (Smith and Wilen 2002), while the potential negative implications of fleet reduction through autonomous adjustment on employment in coastal communities have stalled the implementation of management strategies aimed at improving economic efficiency in some cases (Khalilian *et al.* 2010). Social licence to operate may also be negatively affected by unintended outcomes of management. For example, in some cases, increases in discarding have been associated with ITQ management, particularly in multispecies fisheries (Branch 2004), although this is not necessarily the case (Chu 2009). While discarding is potentially an economically optimal strategy (Anderson 1994; Pascoe 1997), discards are generally viewed by society as an undesirable outcome of harvesting within fisheries (Abbott and Wilen 2009) and many jurisdictions internationally have undertaken efforts to reduce or eliminate discards (e.g. Condie *et al.* 2014).

Despite the recognition of multiple objectives of fisheries management in most jurisdictions internationally (Stephenson *et al.* 2017; Benson and Stephenson 2018), harvest strategies, where tested *a priori*, are usually just tested against just biological and, in some instances, economic target reference points (Sainsbury *et al.* 2000). Further, most management strategy evaluations are undertaken on a species-by-species basis, with relatively few studies undertaking a multi-species-based analysis (Punt *et al.* 2016). Technical interactions in multispecies fisheries obfuscate the potential effectiveness of harvest control rules, which are generally based on achieving outcomes for individual species within the multispecies mix. The aim of this study was to investigate the potential effect of different harvest strategies for a multispecies, multigear fishery against a set of multiple objectives. A bioeconomic model of a multispecies, multifleet fishery was developed and parameterised based on an Australian multispecies, multifleet fishery. A range of different harvest strategies were tested, and the key outcomes in terms of fishery profitability, stock levels, fleet size and discarding were examined over a 20-year period.

This paper is presented as follows: firstly, a description of model assumptions and structure is outlined. Secondly, an overview of the case study fishery and the range of harvest strategies being examined are summarised. Thirdly, the results of the analysis are detailed and, lastly, the management implications are discussed.

2. The multispecies, multimetier bioeconomic model

2.1 Modelling multispecies and multifleet fisheries using metiers

In a multispecies fishery exploited by a number of different fishing fleets, catch composition for a given species stock abundance composition may vary depending on the gear, area and/or time (i.e. season) fished. Changes in fleet composition will affect the catch composition, while vessels within a particular fleet can alter their catch composition through altering their fishing location.

The concept of a 'metier' is useful in capturing these interactions in a bioeconomic model. A metier represents a discrete fishing activity that is defined spatially (and in some cases temporally), by fishing gear and by key species targetted. Achieving maximum sustainable economic returns from a fishery requires not only an appropriate fleet size, but also an appropriate fleet structure and distribution of fishing activity. The use of metiers in bioeconomic models to represent fleet activity is relatively common in European models (Biseau 1998; Pascoe and Mardle 2001; Ulrich *et al.* 2002a, b; Ulrich *et al.* 2007; Pelletier *et al.* 2009) and has also previously been applied to Australian (Ziegler 2012) and New Zealand (Marchal *et al.* 2009) fisheries.

The economic target reference point (maximum economic yield or MEY) is a long-run equilibrium concept. It is where the fishery aims to be. To achieve MEY, harvest strategies, and their associated harvest control rules (HCRs), provide a set of management responses to move the fishery from its current (often disequilibrium) position to the long-term equilibrium. To assess these different strategies, two separate bioeconomic models were required. The first is developed to estimate the long-run equilibrium levels of fishing effort in each metier, and equilibrium catch and biomass of each species that maximise overall fishery profits, defining the economic targets. From this, the optimal fishing mortality[1] (f_{MEY}) for each species and metier can be derived.

These form the basis for setting total allowable catches (TACs) in the second model, a dynamic simulation model, that estimates the ability of the harvest strategy to achieve the long-run targets over a 20-year period. In this second model, TACs were set for each species given a range of potential alternative harvest strategies and HCRs. The model allows fishers to adjust

[1] Fishing mortality represents the fraction of the stock harvested.

their fishing effort in each metier in response to the short-term incentives created by the set of imposed TACs and the efficiency of quota markets (i.e. quota transferability), and estimates how these changes lead to long-term outcomes over time.

2.2 Long-run static equilibrium optimisation model

The long-run static equilibrium optimisation model (LRM) was developed to determine the level of fishing mortality, fleet structure and biomass level that maximises sustainable fishery profits (i.e. MEY). This model does not take into account the initial/current state of the stocks nor the time taken to reach equilibrium levels of stock size and profits. However, it provides estimates of the target reference points that the fishery should aim to achieve in the long term.

The LRM is based on an exponential equilibrium surplus production model (Fox 1970), where the equilibrium catch (C_i) of the key species i is given by:

$$C_i = K_i\left(\sum_m q_{i,m}E_m\right)\exp\left(-\sum_m q_{i,m}E_m/r_i\right) \tag{1}$$

where r_i is the instantaneous growth rate of species i, K_i is the carrying capacity of species i, $q_{i,m}$ is the catchability coefficient of species i in metier m, and E_m is the level of effort (in shots) applied to metier m. The key model parameters are provided in the Supporting Information.
Catch in Equation (1) is estimated at the fishery level based on the total effort applied to the stock. The catch of the key species within each metier ($C_{i,m}$) is approximated by the contribution of that metier to overall fishing mortality, given by:

$$C_{i.m} = \frac{q_{i,m}E_m}{\left(\sum_m q_{i,m}E_m\right)}C_i \tag{2}$$

The model is solved as a non-linear optimisation problem with the objective function:

$$\begin{aligned}\underset{E}{\text{Max}}\,\Pi = &\sum_{i,m} p_i(1-\text{cw}_m-\text{mkt}_m)C_{i,m}\\ &-\sum_m(\text{fuel}_m+o_m)E_m-\sum_m(f_m+v_m)V_m\end{aligned} \tag{3}$$

where Π is the long-run equilibrium level of total fishery profits at MEY, p_i is the price of species i (assumed constant and the same for all metiers, and includes a value for ‘other’ species), cw_m is the crew share of revenue paid by vessels operating in metier m, mkt_m is the marketing cost as a share of revenue paid by vessels operating in metier m, fuel_m is the fuel cost per shot by a vessels operating in metier m, o_m is other running costs per day by vessels operating in metier m, f_m is the annual fixed costs associated with a boat operating in metier m, v_m is the user cost of capital (here defined as total vessel capital times a depreciation rate of 2.6 per cent plus an opportunity cost of capital of 5 per cent), and V_m is the number of vessels operating in metier m (estimated from the level of fishing effort E_m and the average number of shots per vessel). As vessels may operate in more than one metier, fractional vessel numbers are permitted in the model (e.g. a trawl boat may operate in potentially six different metiers, although in practice this is not likely to be the case).

The LRM determines the level of effort in each metier that maximises total fishery profits (E_{MEY}) across all species. The catch of each species at this level of effort is effectively the maximum economic yield of that species.

The fishing mortality associated with each species at MEY (f_{MEY}) is given by:

$$f_{\text{MEY}_{i,m}} = q_{i,m}\hat{E}_m \tag{4}$$

at the metier level ($f_{\text{MEY}_{i,m}}$) and

$$f_{\text{MEY}_i} = \sum_m q_{i,m}\hat{E}_m = \sum_m f_{\text{MEY}_{i},m} \tag{5}$$

at the species level, where $\hat{E}_m$ is the optimal level of fishing effort in metier m.

2.3 Dynamic simulation model

The 'simulation' model was developed as a recursive optimisation model, which captures realistic fisher behaviour for multispecies, multimetier quota fisheries. In the model, TACs for year t are set based on a given HCR (described below) and the prevailing fish stock conditions. An optimisation routine is used to allocate fishing effort between the set of metiers in order to maximise short run profits based on the incentives and constraints faced (indirectly reflecting fisher behaviour). Each year is assessed separately. Stock biomasses in the following year (t + 1) are then derived from the natural growth in the biomass less the catch taken in the previous year t, which in turn are used determined the following year's TACs (and so on).

For a given metier m, the catch of species i during year t (C_{i},m, t) in the simulation model is given by:

$$C_{i,m,t} = q_{i,m}E_{m,t}B_{i,t} \tag{6}$$

where $q_{i,m}$ is the catchability coefficient relating to species i in metier m, $E_{m,t}$ is the level of effort expended in each metier m during year t and $B_{i,t}$ is the level of biomass of species i in year t. In the simulation model, effort in each metier is constrained to change no more than 20 per cent from the previous year (t) (i.e. $0.8E_{m,t-1} \leq E_{m,t} \leq 1.2E_{m,t-1}$) with the level in the initial year based on the observed level of effort in the base year of the model (i.e. 2015). This constraint is imposed to reflect a degree of inertia in the fishery and to prevent large unrealistic changes in effort allocation between years. Studies of fleet behaviour suggest that habits are a major factor influencing effort allocation even in the face of changes in economic incentives (Holland and Sutinen 2000; Hutton *et al.* 2004; Pascoe *et al.* 2013).

A TAC is set for each species at the level of catch associated with f_{MEY} derived from the equilibrium optimisation model, such that the TAC for species i in year t ($TAC_{i,t}$) is given by:

$$\mathrm{TAC}_{i,t} = f_{\mathrm{MEY}_i} B_{i,t} \tag{7}$$

The metier level TAC for species i in year t ($\mathrm{TAC}_{i,m,t}$) is correspondingly given by:

$$\mathrm{TAC}_{i,m,t} = f_{\mathrm{MEY}_{i,m}} B_{i,t} \tag{8}$$

2.3.1 Quota trading

Two quota trading options were considered in the analysis: perfect transferability where quota for a species could transfer to one metier to another; and imperfect quota transferability where quota could (implicitly) transfer between vessels within a metier but could not transfer between metiers. These reflect possible extreme ends of the transferability spectrum, with actual (true) transferability most likely somewhere between these two alternatives.

With perfect quota transferability, fishing mortality targets at the metier level are updated in the simulations, such that

$$f_{\mathrm{MEY}_{i,m}} = f_{\mathrm{MEY}_i} \left(C_{i,m,t-1} / \sum_m C_{i,m,t-1} \right), \tag{9}$$

with allocation in the base year based on the observed catches in each metier. Total catch is still constrained by the fishery level total fishing mortality; it is just the allocation of this fishing mortality between metiers that is adjusted. Trading is ‘perfect’ in the sense that it is assumed that those metiers which needed additional quota in the previous year were able to obtain this quota.

2.3.2 Under-catch and discarding

The model allows for discards and quota under-catch to occur when the TAC does not perfectly align with catch composition (like the actual situation that occurs in most fisheries). Discard of each species i in each metier m during year t (D_i,m,t) is the difference between the pre-defined TAC and catch, while under-catch is the difference between catch and TAC where the former is less than the latter. These are given by

$$D_{i,m,t} = \max\left[0, \left(C_{i,m,t} - \mathrm{TAC}_{i,m,t}\right)\right] \quad (10a)$$

$$U_{i,m,t} = \max\left[0, \left(\mathrm{TAC}_{i,m,t} - C_{i,m,t}\right)\right] \quad (10b)$$

From Equation (10a), discards are positive if catch exceeds the TAC, otherwise they take the value of zero. Conversely, from Equation (10b), under-catch is positive when the TAC exceeds total catch.

2.3.3 Economic components

Revenue is estimated initially at the metier level, before aggregation to total fishery level. This is because some vessel costs are related to revenue, with this relationship varying by metier (as it determined by the gear used in that metier). Metier level revenue ($R_{m,t}$) in year t is given by:

$$R_{m,t} = \sum_i p_i\left(C_{i,m,t} - D_{i,m,t}\right) \quad (11)$$

where p_i is the price of species i (including 'others'), assumed to be constant in real terms over the duration of the simulation. Total fishery revenue (R_t) is given by $R_t = \sum_m R_{m,t}$.

Fishing costs are assumed to include both fixed and variable costs. Some costs, such as those associated with crew and marketing, vary based on revenue, while other costs, such as fuel and other running costs, vary with fishing effort directly. Fishing costs in year t for each metier (CST_m,t) were estimated by

$$\mathrm{CST}_{m,t} = \sum_i (\mathrm{cw}_m + \mathrm{mkt}_m)p_i C_{i,m,t} + (\mathrm{fuel}_m + o_m)E_{m,t} + (f_m + v_m)V_m \quad (12)$$

where parameter values are previously defined (Equation 3). The number of vessels in each metier is derived from the level of fishing effort (e.g. total shots) divided by the average shots per vessel. This effectively implies fractions of vessels within each metier, which does not create an unrealistic distortion in the analysis, since vessels operate across metiers in a year, and costs are gear-specific.

Annual fishery profit at the metier level in year t ($\pi_{m,t}$) is given by:

$$\pi_{m,t} = R_{m,t} - \mathrm{CST}_{m,t} \quad (13)$$

and the net present value (NPV) of profits over the period of the simulations is given by:

$$\mathrm{NPV} = \sum_t \sum_m \frac{\pi_{m,t}}{(1+r)^{t-1}} \tag{14}$$

The model does not determine the optimal trajectory over time, but determines how fishing effort and catch changes in each year in response to the prevailing TACs, with the NPV representing the discounted value of this flow of short run annual optimisations.

2.3.4 Stock dynamics

The stock dynamics is based on the dynamic form of the Fox (1970) model, given by:

$$B_{i,t+1} = B_{i,t} + B_{i,t} r_i \left(\frac{K_i}{B_{i,t}} \right) - \sum_m C_{i,m,t} \tag{15}$$

The biomass in the first year ($B_{i,0}$) is the estimated biomass in 2015.

2.4 Model optimisation methods

We use evolutionary optimisation approaches (i.e. genetic algorithms), using the DEoptim package in R (Mullen *et al*. 2011; R Core Team 2012), to estimate the global optimums for each model run. Both the long-run optimisation model and the short-run effort allocation models (given existing biomass and TACs) are highly non-linear, and as such, are subject to problems of local optima and also non-optimal outcomes using standard non-linear programming techniques. Using evolutionary approaches overcomes these problems, but are relatively slow at reaching the optimum. These approaches have been used previously in fisheries bioeconomic modelling where a large number of non-linearities exist (Mardle and Pascoe 2000; Mardle *et al*. 2000).

2.5 Comparing scenarios against multiple objectives

The model output included the NPV of fishery profits and total (cumulative) discards over the 20-year period; and a measure of the biomass and total fleet size at the end of the 20-year period. The NPV of the discards was estimated by multiplying the estimated quantity discarded for each species by their relevant price and discounted over the period of the simulation. Similarly, the biomass quantity estimated for each species was also multiplied by the price per species to estimate a total 'value' of the natural capital stock at the end of the simulation period.

In a multi-objective context, fleet reduction and discards can be considered as undesirable outcomes from any choice of a HCR, while profits and stock improvements can be seen as desirable outcomes. Without explicit weights to determine an overall 'best' outcome, an alternative approach was needed. The approach adopted in this paper was to use data envelopment analysis (DEA), to 'integrate' over both desirable and undesirable outcomes (Seiford and Zhu 2002). The DEA model can be given by:

$$\begin{aligned}
&\max \theta \\
&s.t. \\
&\sum_j z_j x_{i,j} \geq \theta x_{i,0} \quad \forall i \\
&\sum_u z_j y_{u,j} \leq y_{u,0} \quad \forall u \\
&\sum_j z_j = 1 \\
&z_j \geq 0
\end{aligned} \tag{16}$$

where θ is a measure of the degree to which desirable outputs could be expanded without increasing undesirable outputs, and hence $1/\theta$ is a measure of the 'efficiency' of the scenario; $x_{i,j}$ is the level of the desirable output i produced by scenario j; $y_{u,j}$ is the level of the undesirable output u produced by scenario j; and z_j is the weight attached to each scenario j. The measure is estimated for each scenario, where $x_{i,0}, y_{i,0}$ are the desirable (i.e. profits and biomass) and undesirable (discards and fleet reduction) outputs for the scenario being examined.

3. Application to a case study fishery

3.1 The Australian policy setting

Developing harvest strategies to achieve multiple management objectives is a current issue in Australian fisheries management (Pascoe *et al*. 2016). A key objective of the Australian Fisheries Management Act 1991 is 'maximising net economic returns to the Australian community from the management of fisheries', which has been interpreted as achieving the biomass that, on average, produces maximum economic yield (B_{MEY}) in the Commonwealth Fisheries Harvest Strategy, although this Strategy also requires managers to consider social impacts, as well as impacts on recreational and indigenous fishers (Department of Agriculture and Water Resources 2018b). The Policy does not specify how social impacts are to be considered, but recognised the role the fishing sector has in providing employment in regional areas (Department of Agriculture and Water Resources 2018b). Minimising discarding is also an explicit objective of the Commonwealth Fisheries Harvest Strategy. At the same time, a separate bycatch policy has been developed with the aim of reducing fisheries impacts on bycatch species (Department of Agriculture and Water Resources 2018a).

Central to achieving any objective is the need to identify the appropriate target level of catch, biomass and effort that are associated with this objective. In Australian Commonwealth fisheries, target reference points (TRPs) have been based on the ratio of B_{MEY} relative to the biomass at maximum sustainable yield (MSY) or relative to the unexploited level (B_0). A single-species approach does not account for technical interactions (and ecological interactions) that occur in multispecies fisheries. For multispecies fisheries, deriving appropriate economic-based target reference points is a complex problem (DAFF 2013). For many multispecies fisheries, relatively little information is known about the population dynamics of some of the species. In such cases, a default proxy target reference point of $B_{MEY} = 1.2 B_{MSY} = 0.48B_0$ (where B_{MSY} is also assumed to be $0.4B_0$) has been set under the Commonwealth Fisheries Harvest Strategy Policy Guidelines (Department of Agriculture and Water Resources 2018c). However, a mis-specified set of TAC for an individual species within a multispecies fishery may lead to increases of discarding and lower economic performance than a more optimal combination. These problems are further magnified when a species is taken by a range of different fishing gears. These different subfleets may be at different stages of evolution, with some overcapitalised, and others under-capitalised; and harvesting stocks some of which may be underfished and others overfished. In a multispecies, multigear fishery, the corresponding set of TACs (one for each species) will influence fleet adjustment over time, with mis-specified TACs potentially resulting in suboptimal (i) economical fleet(s), (ii) stock levels and (iii) discard rates, respectively.

3.2 Scenarios

A range of different HCRs (Table 1) were developed for consideration. These included setting the TACs each year on:

1. A constant fishing mortality rate estimated using the long-run equilibrium model that maximised long-run fleet economic profits;
2. The traditional ‘hocky stick’ HCR, where the long-run optimal fishing mortality rate was applied if the biomass was greater than or equal to the TRP biomass, but below this level of biomass (i.e. $B < B_{MEY}$) the fishing mortality rate was reduced to the limit reference point (the lowest level of biomass considered acceptable), at which point a zero fishing mortality was imposed (see Figure 1); and
3. A ‘linear’ HCR where fishing mortality continued to increase linearly above the estimated long-run f_{MEY} if the biomass was above the TRP biomass level, but followed the ‘hocky stick’ adjustment if $B < B_{MEY}$ (Figure 1).

Table 1 Summary of scenarios applied in the final analysis

	Description
Baseline scenarios	
Constant fishing mortality (long-run equilibrium model-estimated f_{MEY})	
S1	Maximises total fishery profits assuming 'perfect' transfer of quota
S2	Maximises total fishery profits assuming imperfect transfer of quota; that is, quota transfer is permitted only within a metier but not across metiers.
Harvest control rules (HCRs)	
Imperfect quota market, hocky stick HCR	
S3	F varies each year based on 'hocky stick' HCR; long-run equilibrium model-estimated f_{MEY}
S4	F varies every three years based on hocky stick HCR; model-estimated f_{MEY}
S5	F varies each year based on 'hocky stick' HCR; proxy $f_{MEY} = 0.8f_{MSY}$ (all quota species)
S6	F varies each year based on 'hocky stick' HCR; proxy $f_{MEY} = 0.8f_{MSY}$ for primary species; f_{MSY} for others
Imperfect quota market, linear HCR (f increases above f_{MEY})	
S7	F varies each year based on linear HCR; based on model-estimated f_{MEY}
S8	F varies each year based on linear HCR; based on proxy $f_{MEY} = 0.8f_{MSY}$ (all quota species)
Perfect quota market, linear HCR	
S9	F varies each year based on linear HCR; based on model-estimated f_{MEY}
Quota on only a few species	
Imperfect quota market, constant fishing mortality	
S10	f_{MEY}-based total allowable catch (TAC) set for only the top three species by catch value for each gear type (based on contribution to gross value of production (GVP)), resulting in seven species overall (when considering all gears).
S11	f_{MEY}-based TAC set for only the top two species by catch value for each gear type (based on contribution to GVP), resulting in five species overall.
S12	f_{MEY}-based TAC set for only the top species by catch value for each gear type (based on contribution to GVP).

In addition, initial baseline runs included a comparison of different assumptions of quota transferability. The effects of limiting quotas to a subset of species only were also examined by setting TACs for non-key species to an arbitrary high level (so that they were effectively not binding); mimicking a management approach that reflects minimal regulation and the fact that attempting to finely control fishing mortality of each and every species at each moment in time in a large complex fishery is not cost-effective.

The effect of setting TACs only every three years (rather than annually) is also considered. Finally, target biomass levels are also estimated using the proxy measure approaches rather than from the long-run equilibrium model to examine the influence of potential errors in the biomass targets due to the simpler approach on the fishery outcomes.

3.3 Parameterisation of the model

The model was parameterised using data for the Australian Southern and Eastern Scalefish and Shark Fishery (SESSF). The SESSF was Australia's first multispecies fishery to move to ITQs. The fishery contains a number of

Table 2 Metiers and species/stocks included in the model and relative importance of each metier in terms of total species catch (%)

Common name	Species code	Metier										
		Inshore trawl NSW	Inshore trawl Eastern Bass Strait (EBS)	Trawl offshore NSW	Trawl offshore EBS	Danish seine EBS	Danish seine Western Bass Strait (WBS)	Blue grenadier trawl	Gillnet EBS	Gillnet WBS	Hook and line	Tasmanian trawl
		T_In_NSW	T_In_EBS	T_Off_NSW	T_Off_EBS	DS_EBS	DS_WBS	BGren	GillE	GillW	Hook	T_Tas
Blue Warehou	TRT	*	-	***	***	-	**	-	-	-	-	**
Flathead	FLT	**	*	**	*	-	***	-	-	-	-	**
Gemfish	GEM	*	*	*	*	-	-	*	-	-	**	***
John Dory	DOJ	***	-	***	-	-	**	-	-	-	-	*
Ling East	LIG_E	*	**	*	***	-	-	**	-	-	-	-
Ling West	LIG_W	-	-	-	-	-	-	-	-	-	***	-
Mirror Dory	DOM	*	***	*	**	-	-	-	-	-	-	***
Morwong East	MOW_E	**	-	***	*	-	*	-	-	-	**	***
Morwong West	MOW_W	-	-	-	-	-	-	-	-	*	-	***
Ocean Perch	REG	*	***	-	***	-	-	-	-	-	*	**
Ribaldo	RBD	-	-	-	**	**	**	*	-	-	***	*
Silver Trevally	TRE	***	-	-	-	*	-	-	-	-	-	-

Table 2 (*Continued*)

Common name	Species code	Metier										
		Inshore trawl NSW	Inshore trawl Eastern Bass Strait (EBS)	Trawl offshore NSW	Trawl offshore EBS	Danish seine EBS	Danish seine Western Bass Strait (WBS)	Blue grenadier trawl	Gillnet EBS	Gillnet WBS	Hook and line	Tasmanian trawl
		T_In_NSW	T_In_EBS	T_Off_NSW	T_Off_EBS	DS_EBS	DS_WBS	BGren	GillE	GillW	Hook	T_Tas
Silver Warehou	TRS	-	*	-	**	-	-	**	-	-	-	***
Eastern School Whiting	WHS	*	-	-	-	***	***	-	-	-	-	-
Blue Grenadier	GRE	-	-	-	***	-	-	***	-	-	-	***
Gummy Shark	SHG	-	-	-	-	-	-	*	***	***	***	-
School Shark	SHS	-	-	*	-	-	*	-	***	***	**	-
Blue-Eye Trevalla	TBE	-	-	-	*	-	-	-	-	-	***	-

Note: - Negligable importance (<1% of total species catch); *Minor importance (>1% of total species catch); ** Moderate importance (>10% of total species catch); *** High importance (>20% of total species catch).

subfisheries, several of which were previously managed as separate fisheries. However, given the overlap between fleets and species, the subfisheries were combined into a larger fishery for management purposes in 2003. As a result, the current SESSF is a multispecies, multigear fishery across the south-eastern portion of the Australian Fishing Zone. Further details on the fishery, including the model parameters used, are presented in the Appendix S1.

The model included 18 separate stocks representing 16 separate species (Table 2). Eleven different metiers were also incorporated into the model, covering three different fishing types (trawl, gillnet and hook and line) and different spatial regions of the fishery (e.g. inshore, offshore, Bass Strait, east, west). The fishery also includes a large number of minor species that are caught as incidental by-product. Individually, these species represent only a small contribution to income, but combined represent up to 10 per cent of the revenue from some metiers. Catch of these 'other' species for metier m ($C_{i=o,m}$) was combined and included in the model as a non-linear catch-effort equation, but without a specific dynamic stock model for each species, given by:

$$C_{i=\mathrm{o,m}} = \alpha_{\mathrm{m}} E_{\mathrm{m}} - \beta_{\mathrm{m}} E_{\mathrm{m}}^2 \tag{17}$$

where α_{m}, β_{m} are metier-specific parameters estimated from catch and effort data. This relationship was included in both the long-run equilibrium model and the short-run simulations model.

4. Results

4.1 LRM – estimating B_{MEY} and F_{MEY}

The long-run sustainable maximum profits for the fishery as a whole were estimated to be \$13.9 m per year. For comparison, in 2016–2017, the gross value of production (GVP) in the SESSF was estimated to be around \$72.3 m, from which the total net economic returns as a whole were estimated to be around \$3.9 m, most of which accrued in the trawl sector (Bath *et al.* 2018).

The level of fishing effort (i.e. total shots) required to achieve this is shown in Figure 3 and is compared with the baseline (2015) fishing effort in each metier. Total fishing effort in the base year is higher than the optimal level in most trawl metiers considered, with Danish seine effort lower than optimal in the Bass Strait, but close to optimal in Eastern Bass Strait (Figure 3). The gillnet Western Bass Strait (WBS) effort is close to the optimal level, while the other gillnet, hook and trap metiers are above their optimal level (Table 2).

The associated optimal fleet configuration is shown in Table 3. The model optimises fishing effort at the metier level, and vessel numbers are derived based on this effort and the current average effort per vessel. As a result, the optimal effort involves fractions of vessels rather than whole vessels (e.g. 10.6 east coast trawlers). In reality, while whole boats would be required, although

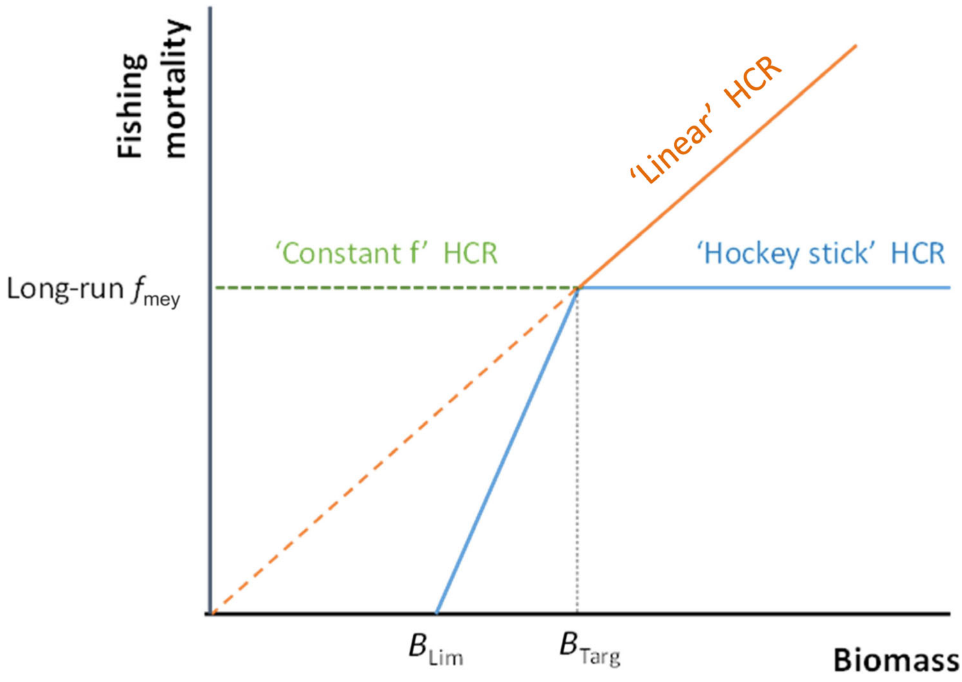

Figure 1 Alternative harvest control rules (HCRs) applied in simulations. For this study, B_{Targ} (the target biomass) was equal to B_{MEY}. B_{Lim} was assumed equal to 20 per cent of B_0. [Colour figure can be viewed at wileyonlinelibrary.com]

potentially some vessels could move between fleets as currently defined for part of the season (e.g. some east coast trawlers could operate part of the year in the Tasmanian trawl).

The optimal fleet configuration involves a larger number of Danish seiners than in the 2015 fleet, although all other fleet segments have fewer vessels than in 2015. Overall, the total optimal fleet size is around half the 2015 fleet (Table 3).

The estimated optimal fishing mortality rate (f_{MEY}) for each species, the associated (optimal) level of biomass, and the estimated biomass level in 2015 (B_{2015}), imputed from the model parameters are provided in Table 4. From this, it can be seen that for some species (e.g. School Shark, SHS), their current biomass is estimated to be substantially lower than the level associated with MEY (i.e. they are currently economically overfished), while for other species the current biomass is greater than the optimal biomass (economically underfished). To achieve MEY, then, requires rebuilding some stocks while reducing others.

4.2 Achieving MEY – Dynamic simulations

The key outputs from the different dynamic simulations are presented in Table 5. The NPV of profits over the 20 simulated years varied from \$82 m to

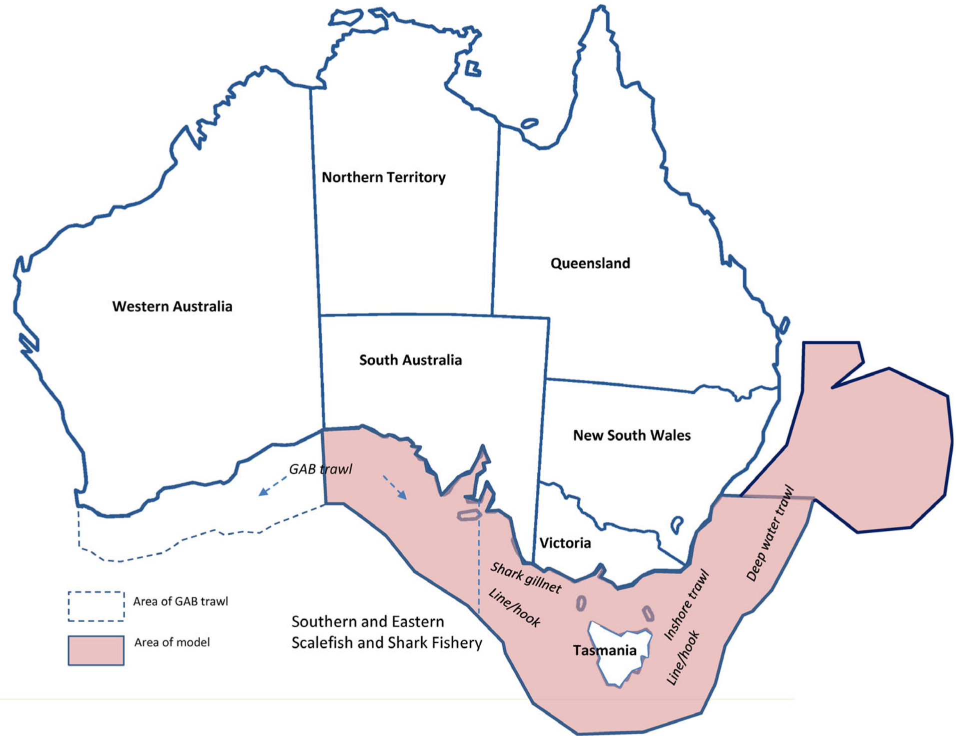

Figure 2 Southern and Eastern Scalefish and Shark fishery. [Colour figure can be viewed at wileyonlinelibrary.com]

$155 m, while the 'value' of the increase in biomass over the same period varied from $9.7 m to $11.8 m (Table 5). The scenarios that were based on the proxy target reference points (S5, S6, S8, S9) generally resulted in the highest NPV of profits over the 20-year period, and the lowest increase in biomass. Also, for many species, the proxy target fishing mortalities were higher than those derived from the model at MEY, results in higher TACs,

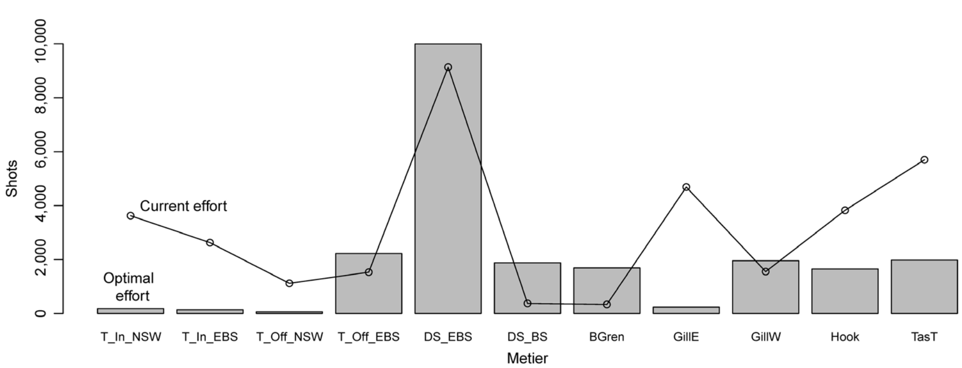

Figure 3 Long-run static profit maximising level of fishing effort by metier (for metier code – see Table 2).

higher catches and greater fishery profits, but lower stock levels and greater levels of discarding (Table 5).

The trade-off between these measures is illustrated in Figure 4. The NPV of fishery profits is strongly negatively correlated with the biomass change. That is, higher catches in earlier years result in higher profits over the 20-year simulated period but a slower stock recovery. The NPV of profits was also negatively correlated with the per cent change in fleet size, with higher profits over the period being achieved by a larger reduction in fleet size. Conversely, a higher NPV of profits was positively correlated with the level of discards.

The DEA analysis resulted in an ‘efficiency’ score of each management scenario (Figure 5). Harvest strategies based on a ‘hocky stick’ control rule (S3–S6) generally performed worse across the different outputs. As might be expected, scenarios assuming perfect quota transferability performed better than those that assumed imperfect quota transferability, for example S1 vs S2; S7 vs S9. Unexpectedly, the scenario based on MEY-based proxy target reference points for all species and a linearly proportional HCR (S8) performed well. Limiting the number of species subject to quota also performed well (S10–S12), although reducing this to just the main species for each gear type (S12) resulted in a less efficient outcome.

5. Discussion and conclusions

The choice of harvest strategy in a multi-objective context is complex when there are trade-offs between the key outcomes of interest to managers, stakeholders and interested public. Without explicit weighting of these objectives, identification of the ‘best’ option is not possible. However, some harvest strategies can be discounted from the onset, as greater desirable outcomes could be achieved using different harvest strategies without increasing the undesirable outcomes. In this regard, the use of DEA allows a more appropriate subset of harvest strategies to be identified, even if objective weights are unavailable. Such an approach has had only limited application elsewhere (e.g. Griffin and Woodward 2011), but can potentially be used to evaluate a wide range of strategies taking into account the competing goals that policymakers may have.

Table 3 The 2015 and long-run optimal fleet configuration

Fleet segment	2015 vessel numbers	Optimal vessel numbers
East coast trawlers	23	10.6
Tasmanian trawl	14	5.1
Danish seiners	14	17.4
Gillnet, Hook and Trap	72	27.9
Total	123	61.0

Table 4 Estimated optimal fishing mortality (f_{MEY}), optimal biomass (B_{MEY}) and 2015 biomass

Species name	Species code	f_{MEY}	B_{MEY} (t)	B_{2015} (t)
Blue Warehou	TRT	0.024	15,719	3,303
Tiger Flathead	FLT	0.087	18,247	22,419
Gemfish	GEM	0.014	39,201	19,539
John Dory	DOJ	0.039	2,198	1,810
Ling East	LIG_E	0.122	9,055	7,306
Ling West	LIG_W	0.057	14,148	13,299
Mirror Dory	DOM	0.095	12,950	12,850
Jackass Morwong East	MOW_E	0.022	28,456	14,276
Jackass Morwong West	MOW_W	0.001	4,422	3,880
Ocean Perch	REG	0.001	2,069	4,014
Ribaldo	RBD	0.526	575	493
Silver Trevally	TRE	0.031	9,767	5,919
Silver Warehou	TRS	0.028	36,351	28,146
Eastern School Whiting	WHS	0.022	11,033	11,848
Blue Grenadier	GRE	0.114	108,122	84,326
Gummy Shark	SHG	0.179	12,322	13,148
School Shark	SHS	0.062	27,418	6,943
Blue-Eye Trevalla	TBE	0.296	1,784	1,663

Table 5 Desirable and undesirable outcomes under each harvest strategy

Scenario	Desirable outcomes		Undesirable outcomes	
	NPV profit ($'000)	NPV biomass value change ($'000)	Reduction in fleet (%)	NPV discards ($'000)
S1	101,300	10,340	26	13,704
S2	87,682	11,599	32	207
S3	81,651	11,751	33	13,966
S4	80,419	11,806	34	15,207
S5	114,971	10,785	23	26,322
S6	116,894	10,684	23	25,083
S7	82,253	11,548	34	22,118
S8	135,930	9,799	20	28,532
S9	154,730	9,768	23	10,455
S10	87,617	11,612	33	231
S11	87,402	11,610	34	190
S12	95,531	11,163	30	5,901
Average	102,198	11,039	29	13,493

Note: NPV, net present value.

In the study, imposing quota on just a subset of species appeared to perform well across the four objectives, with the top two species for each main gear type (by value) appearing to provide the greatest benefit from this option. In contrast, basing management on only the top species for each gear type resulted in a lower overall score. Newman *et al.* (2018) suggested that there be a formal identification of 'indicator' species, determined through a risk assessment, to which individual quota are applied. These indicator species can be chosen based on their: (i) inherent vulnerability, that is

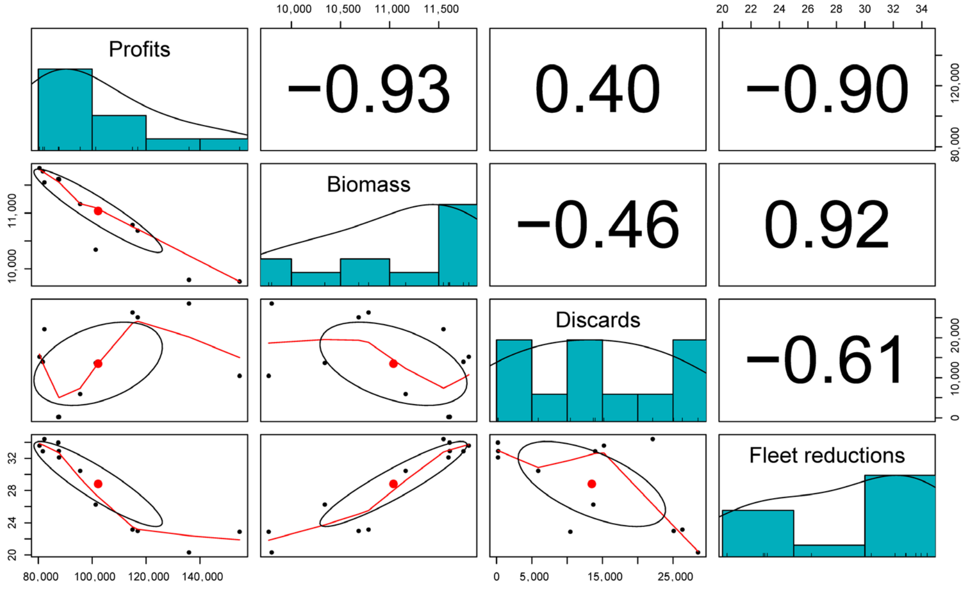

Figure 4 Trade-offs between profits, biomass, discards and fleet reductions across the different harvest strategies. The numbers in the right diagonal of the matrix are the correlation coefficient between *x*-axis and *y*-axis (variables). [Colour figure can be viewed at wileyonlinelibrary.com]

biological attributes; (ii) risk to sustainability, that is stock status; and (iii) management importance, that is commercial prominence, social and/or cultural amenity value of the resource (Newman *et al.* 2018).

The use of a ‘hocky stick’ HCR also appears to be generally less appropriate in multispecies fisheries when trying to move towards a fishery-level MEY. In this case, as is likely to be the case in many multispecies fisheries, some stocks required fishing down while others required rebuilding. While the hocky stick HCR helps with stock recovery, it imposes limitations to the process of stock reduction for those species that are above their target biomass levels. The use of a more linear HCR that allows higher fishing mortality on stocks above their target level moves the fishery closer to an optimal configuration earlier.

Most of the scenarios assumed that quota transferability was imperfect. To some extent, the imperfect quota scenarios represent the ‘worst-case’ outcomes. Kompas and Che (2005) found considerable trade between trawlers and Danish seiners in the SESSF, mostly through leasing rather than permanent transfers. Studies in other southern Australian fisheries (e.g. van Putten *et al.* 2011) found that trade can be restricted by the typical limited range of personal networks. However, van Putten *et al.* (2011) also found that the importance of these networks (and their restrictions on trade) decreased as the quota market evolved, with more non-fishers (e.g. investors, processors) holding a higher share of the total quota. Where the same HCR was imposed with both perfect and imperfect quota transferability, the latter

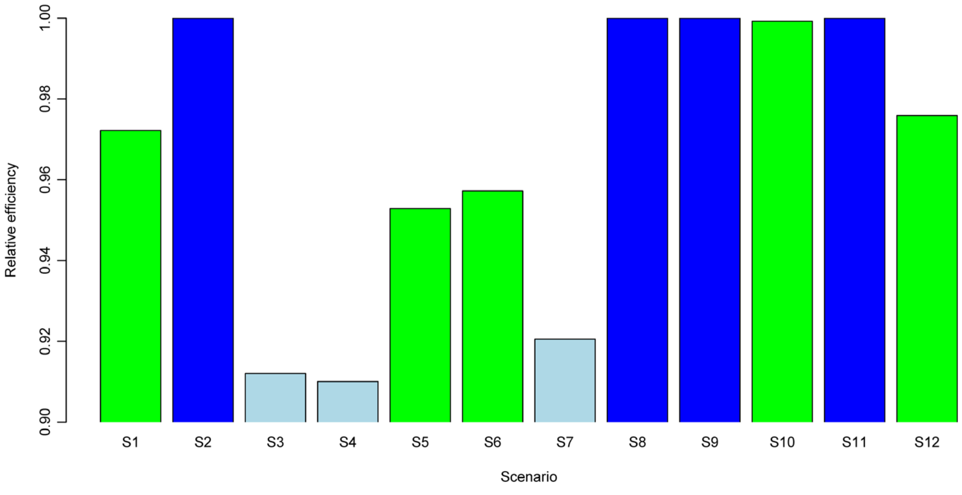

Figure 5 Data envelopment analysis (DEA)-based relative efficiency of each scenario: desirable outputs are NPV profits and NPV biomass, and undesirable outputs are discarding and per cent fleet reduction. Dark blue bars are fully efficient (i.e. score = 1); green bars are between 95 per cent and 99 per cent efficient; light blue bars are <95 per cent efficient. [Colour figure can be viewed at wileyonlinelibrary.com]

generally performed equally or better. This suggests that ensuring quota markets are efficient is not a necessary condition for achieving desirable outcomes when multiple objectives are considered. While greater economic benefits were achieved with perfect quota transferability, these also resulted in a larger reduction in fleet size.

Another complexity in implementing MEY in multispecies fisheries is that catch composition can change through gear change, changes in seasonal or spatial fishing patterns, that is through individual fisher behaviour. Previous studies examining fishers' ability to control output mix in a fishery (Squires 1987; Pascoe *et al*. 2007; Pascoe *et al*. 2010) found that the ability to target some individual species may be limited, but not impossible. However, some studies of fisher behaviour also suggest that apparent targeting behaviour (or a lack of) may be an artefact of the management schemes, and changing management may change this relationship as fishers respond to the new incentives created (Christensen and Raakjær 2006). For example, Woods *et al*. (2015) found that short-term profit maximising behaviour of fishers can affect the utility of the catch–quota balancing regulations used in the Icelandic ITQ system for the multispecies demersal fishery.

Such fisher behavioural changes in response to economic, biological and regulatory conditions can be incorporated into a modelling framework, although there is generally a lack of realistic representation of resource users' behaviour in most existing models (Bunnefeld *et al*. 2011; Fulton *et al*. 2011). In this study, fleets were assumed to respond to short-term economic incentives through adjusting effort levels in the different metiers given the available quota mix. Constraints on the rate of adjustment were assumed (no more than a 20 per cent increase or decrease each year), which would also have affected the outcome. Studies on fleet behaviour in multimetier fisheries are limited. Research into how effort adjusts internally in a fishery in response to changing economic conditions is an area of future importance. If the results from this study are to be 'operationalised' in the actual SESSF, then due consideration (with extensive stakeholder input) must be given to future potential realistic changes in effort per metier (which will meet targets and expectations) in a constantly adaptive framework given the ever-changing biological and economic environment.

The MEY proxy values of the fishing mortality rate, being generally higher than those that were 'optimal' in the longer term, can result in improved economic benefits if used in a harvest strategy in the short- to medium-term. However, as these are not developed taking into account the technical interactions within the fishery, they also result in substantially higher levels of discarding and under-caught quota. As a short-term measure, the use of proxy-based target reference points may provide benefits until more appropriate measures are determined, but as a long-term measure are likely to not achieve the overall fishery objectives.

The results of the study, while based on a parameterisation of the SESSF, are likely to be generically applicable to a wide range of multispecies fisheries. The SESSF was chosen as it is fairly typical of multifleet, multispecies fisheries found all around the world. The model, however, can also be parameterised for other fisheries as required to identify fishery-specific harvest strategies not considered above. A key result of the model that is likely to be broadly applicable is that harvest control rules developed primarily for single-species fisheries (e.g. the hocky stick HCR) may not be as effective when implemented in multispecies fisheries.

Data availability statement

All data used in the analysis are included in the Appendix S1. The model code (in R) is available on request from the authors.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Case study fishery.