ICES Journal of
Marine Science

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

ICES Journal of Marine Science (2021), 78(5), 1599–1613. doi:10.1093/icesjms/fsab057

Flexibility of joint production in mixed fisheries and implications for management

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Briton, F., Thébaud, O., Macher, C., Gardner, C., and Little, L. R. Flexibility of joint production in mixed fisheries and implications for management. – ICES Journal of Marine Science, 78: 1599–1613.

Received 31 July 2020; revised 1 March 2021; accepted 3 March 2021; advance access publication 14 April 2021.

Over the past decade, efforts have been made to factor technical interactions into management recommendations for mixed fisheries. Yet, the dynamics underlying joint production in mixed fisheries are generally poorly captured in operational mixed fisheries models supporting total allowable catch advice. Using an integrated ecological–economic simulation model, we explore the extent to which fishers are likely to alter the species composition of their landings in a mixed fishery managed with individual transferable quotas, the Australian Southern and Eastern Scalefish and Shark Fishery. Our simulations capture three different types of joint production problems, highlighting the flexibility that exists in terms of achievable catch compositions when quota markets provide the economic incentives to adapt fishing practices to quota availability. These results highlight the importance of capturing the drivers of fishing choices when advising TAC decisions in mixed fisheries. We also identify a hierarchy of species in this fishery, with harvest targets set for primary commercial species determining most of its socio-economic performance.

Keywords: fishing behaviour, ITQ, joint production, mixed fisheries, Southern and Eastern Scalefish and Shark Fishery, TAC advice

Introduction

There is now broad recognition that traditional single-species approaches, which still form the basis of most tactical management decisions in fisheries, fall short of addressing the complexities observed in mixed fisheries, where a variety of species are simultaneously caught in fishing operations, due to so-called technical interactions. The issue with setting management targets at the stock level in such fisheries is twofold: first, the objectives are unlikely to be met for all stocks simultaneously, leading to situations of over-quota discards or lost catch opportunities (Ulrich *et al.*, 2011, 2017; Patrick and Benaka, 2013); second, single-species advice fails to account for the overall performance of the mixed fishery, particularly its economic and social dimensions (Dichmont *et al.*, 2008; Rindorf *et al.*, 2017; Hoshino *et al.*, 2018). The nascent development and operationalization of approaches aiming at factoring mixed fisheries interactions into tactical management decisions reflect this growing awareness (Dichmont *et al.*, 2010; Klaer and Smith, 2012; Ulrich *et al.*, 2017; ICES, 2020).

Economists were among the first to argue that knowledge about the technological structure of a multi-output fishery is critical to its successful regulation (Squires, 1987; Kirkley and Strand, 1988; Jensen, 2002). Particularly relevant to the regulator tasked with setting catch limits in a mixed fishery is information about jointness in inputs and substitutability between outputs. In firm production analysis, which aims at establishing the relationship between quantities of factors employed by a firm (also referred to as input to production) and the amount of product obtained (output from production), a technology is said to be non-joint in input quantities when the production of single outputs can be represented as independent functions of inputs. Non-joint technologies in mixed fisheries represent one end of the regulator's spectrum where catch limits on individual species can be set independently as they relate to independent production processes. Although the regulator of a mixed fishery may seldom encounter such a situation, since production in such a fishery has generally been shown to be non-separable in inputs (Jensen, 2002), catch limits in mixed fisheries are still mostly set using single-species approaches, i.e. as if their catch was the result of independent production processes.

As highlighted by Pascoe *et al.* (2007), rejecting the assumption of separable production does not necessarily mean that the outputs are produced in fixed proportions. The latter could be referred to as purely joint production, and would represent the other end of the spectrum. Outputs can be substitutable to some extent. In this regard, the analysis of production functions in mixed fisheries has often evidenced fishery-specific (Kirkley and Strand, 1988; Jensen, 2002; Pascoe *et al.*, 2007, 2010) and sometimes fleet-specific (Pascoe *et al.*, 2007) levels of substitutability between species, hereby justifying the need to relax the assumption of purely joint production usually encountered in mixed fisheries management advice, for example, by allowing effort allocation to change across *metiers* [defined in EU (2008, 2010) as "a group of fishing operations targeting a similar (assemblage of) species, using similar gear, during the same period of the year and/or within the same area and which are characterised by a similar exploitation pattern"], or enabling variable catchabilities, as suggested in Ulrich *et al.* (2011). There is today a critical need for the science guiding the management of mixed fisheries to fully grasp the reality of their operation, which lies somewhere along the gradient between a collation of independent production processes and purely joint production.

The extent to which multi-species catch composition is flexible at the individual level is the result of: (i) the possibility for fishers to alter their catch composition by changing their fishing practices (i.e. how they allocate their fishing effort among metiers) and (ii) their incentive to do so. The possibility for fishers to change what they catch is constrained by the technology available to them and the ecosystem in which they operate. Consequently, margins in selectivity can be classified as either technical, relating to improving the selectivity of fishing gears or practices, or institutional, pertaining to providing incentives to fish more selectively, be they market or social-based (Pascoe, 2010; Abbott *et al.*, 2015).

This work explores the extent to which institutionally-driven incentives, here the lease value of quota units, can interact with technical constraints to determine the effective response in terms of output substitution. An integrated ecological–economic model representing the dynamics of the fishery, including different fishing behaviours and incentives, was used to investigate the potential flexibility of catch composition resulting from changes in fishing practices in a fishery managed under Individual Transferable Quotas (ITQs): the Australian Southern and Eastern Scalefish and Shark Fishery (SESSF). Results of different scenarios are assessed in terms of Total Allowable Catch (TAC) uptake and economic performance of the fishery. Management implications relating to the possibility to simultaneously reach single-species reference points are examined, as well as whether management could rely on the definition of target reference points on a subset of species only.

The SESSF

The SESSF is a multi-sector and multi-species fishery that operates in Australian federally-managed waters as well as some state waters under specific arrangements, exploiting from shallow to deep-water fishing grounds. The SESSF is currently the largest Commonwealth fishery in terms of landed weight, and the second most valuable, accounting for 20% of the gross value of production (GVP) of Australian federal fisheries (Patterson *et al.*, 2017). Around 30 species of shark and scalefish are commercially harvested in the area, with a dozen accounting for more than 75% of the fishery's GVP. Management in the fishery primarily relies on output controls on the key commercial stocks and several by-product species. TACs are currently determined for 34 stocks based on single-species target and limit reference points and allocated as ITQs. Introduced in 1992, ITQs brought flexibility in the fishery (Connor and Alden, 2001) and a growing activity in the quota lease market indicates falling transaction costs facilitating the reallocation of quota units (Knuckey *et al.*, 2018). As described in the Harvest Strategy Policy for Australian federal fisheries (Department of Agriculture and Water Resources, 2018), management of the fishery aims at maximizing the fishery's profits using Maximum Economic Yield (MEY) target reference points (B_{MEY}) defined relative to Maximum Sustainable Yield (MSY) reference points ($B_{MEY} = 1.2B_{MSY}$) or pre-exploitation stock biomasses ($B_{MEY} = B_{48} = 0.48B_0$ when using $B_{40} = 0.4B_0$ as a proxy for B_{MSY}). Yet, in order not to restrict the ability to achieve MEY for stocks of primary commercial importance, B_{MSY} (or B_{40} proxy) has become the target biomass for some secondary commercial stocks (Patterson *et al.*, 2017). The Harvest Strategy Policy also requires that all stocks be maintained above a limit biomass reference point (B_{lim}), where the risk to the stock is regarded as unacceptable. By default, this limit reference point is equal to 20% of pre-exploitation biomass (B_{20}). As illustrated in Figure 1, Harvest Control Rules (HCRs) used to recommend catch limits take the form of hockey-stick functions involving three reference points: B_{lim}, the limit biomass, B_{targ}, the

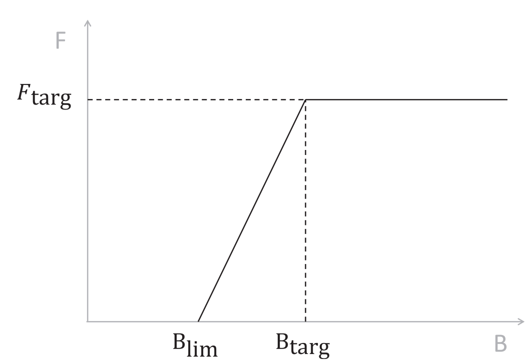

Figure 1. HCR in the Southern and Eastern Scalefish and Shark Fishery.

target biomass, and F_{targ}, the fishing mortality associated with an equilibrium biomass of B_{targ}.

The fishery is divided into four sectors represented by different gear types targeting specific group of species, namely the Gillnet Hook and Trap Sector (GHTS), the Commonwealth Trawl Sector (CTS), the Great Australian Bight Trawl Sector (GABTS), and the East Coast Deep-Water Trawl Sector (ECDWTS). In this work, we focus on the first two since the latter two do not interact with other sectors and are managed independently. In 2015, there were 123 active vessels in the two sectors considered, with 110 of these vessels landing more than 1 ton and employing a total of 340 crew members [estimation based on personal communication from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)].

The fishery is characterized by consistent quota latency, with the TACs of many species being regularly under-caught (Knuckey *et al.*, 2018). This work investigates how a combination of institutionally-driven incentives, here the lease value of quota units, can interact with technical constraints to determine TAC uptake in this mixed fishery. We explore the extent to which the joint production of three selected pairs of scalefish species is flexible, given the possibility for fishers to operate in different metiers characterized by different species compositions. These pairs, referred to as sub-fisheries in the remainder of the text, represent various types of joint production summarized in Table 1. Figure 2 shows the spatial and depth distribution of the studied sub-fisheries, namely:

- flathead (*Neoplatycephalus richardsoni* and four other species) and john dory (*Zeus faber*; sub-fishery A): flathead is found in continental shelf and upper-slope waters in the eastern part of the fishery with most of its commercial catch coming from trawlers and Danish seiners at depths between 50 and 200 m on the continental shelf (Patterson et al., 2017). Similarly, john dory inhabits coastal and continental shelf waters with most of its catch coming from 50 to 200 m depth. John dory is generally not a targeted species with most of its catch being taken in the eastern part of the fishery when targeting flathead or catching a mix of species on the continental shelf.
- flathead and jackass morwong (*Nemadactylus macropterus*—eastern stock; sub-fishery B): like flathead, jackass morwong is found in southern and eastern continental shelf and upper-slope waters, with greater abundance in the shallower part of the range, at depths between 100 and 200 m (Patterson et al., 2017). In the eastern part of the fishery, flathead and jackass morwong are therefore at the heart of technical interactions, with jackass morwong mostly coming as a by-product of trawl and Danish seine operations targeting flathead. It is however possible for trawlers to target jackass morwong in specific areas, hence giving them the possibility to increase the proportion of jackass morwong in their catch.
- flathead and pink ling (*Genypterus blacodes*—eastern stock; sub-fishery C): pink ling mostly occurs at depths between 200 and 1000 m and is frequently targeted by trawlers, and longliners between 300 and 700 m on the continental slope. As a consequence, flathead and pink ling are almost never caught during the same fishing operations, although they can be harvested by the same vessels. This is, for instance, the case of trawlers operating in the east that can either target flathead or pink ling depending on the fishing area. Danish seiners are restricted to shallow fishing grounds and hence do not catch pink ling, and longliners operate too deep to catch significant amounts of flathead.

These four species do not have the same economic contribution to the fishery, with flathead and pink ling being primary commercial species [respectively, accounting for 44% and 11% of CTS and GHTS scalefish GVP in 2015 (Patterson *et al.*, 2017)] and jackass morwong and john dory secondary commercial species (respectively, 1% and 2% of GVP). Current biomass (resp. fishing mortality) targets for these stocks are: $1.2B_{MSY}$ ($0.8F_{MSY}$) for flathead (the MEY target based on the estimation of MSY), B_{48} (F_{48}) for pink ling and jackass morwong (the MEY target based on MSY proxy), and B_{40} (F_{40}) for john dory (the MSY proxy; Patterson *et al.*, 2017). In 2015, the primary commercial species, flathead and pink ling, were constraining activity in the fishery, with TAC uptake rates of, respectively, 94% and 82% (because of frictions in quota markets, TACs very rarely get fully caught in the SESSF, and uptake rates above 80% commonly indicate TACs constraining the fishery). That year, the TACs of jackass morwong and john dory remained largely under-caught, with uptake rates of, respectively, 21% and 46%.

Methods

IAM bio-economic model

Simulations were run with the integrated multi-species and multi-metier individual-based model IAM (Nielsen *et al.*, 2018), which has been previously described in (Merzereaud *et al.*, 2011; Bellanger *et al.*, 2018; Macher *et al.*, 2018; Briton *et al.*, 2019). The present work builds on the version described in Briton *et al.* (2019), which models the dynamics of mixed fisheries under output controls, with TACs set according to a HCR conditioned by fishing mortality targets specified as model inputs. The model runs with an annual time step. For the purpose of the present work, this version was augmented with a module simulating the dynamics of ITQ lease markets in multispecies fisheries. A synthetic presentation of the model is given, and the reader is

Table 1. Selected pairs of species at the heart of technical interactions in the SESSF.

Sub-fishery	Species 1	Species 2	Available metiers		
			Targeting species 1	Mix species 1 and 2	Targeting species 2
A	Flathead (primary)	John Dory (secondary)	Yes	Yes	No
B	Flathead (primary)	Jackass Morwong (secondary)	Yes	Yes	Yes
C	Flathead (primary)	Pink Ling (primary)	Yes	No	Yes

Their commercial importance is indicated in parenthesis. Whether it is possible to target each species and/or simultaneously catch them in "mixed" metiers was deduced from the metier identification described in Supplementary Material A.

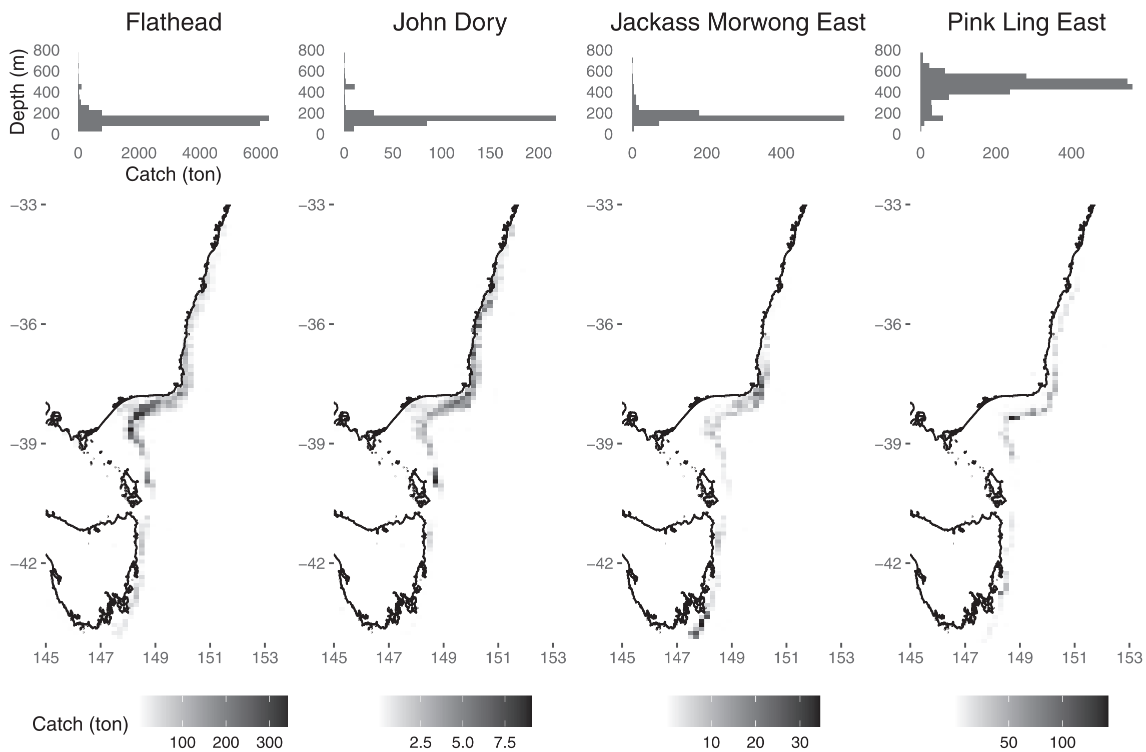

Figure 2. Spatial and depth distribution of the landed catch of the stocks involved in the studied sub-fisheries. From left to right: flathead, john dory, jackass morwong (eastern stock), and pink ling (eastern stock).
Source: Logbook data.

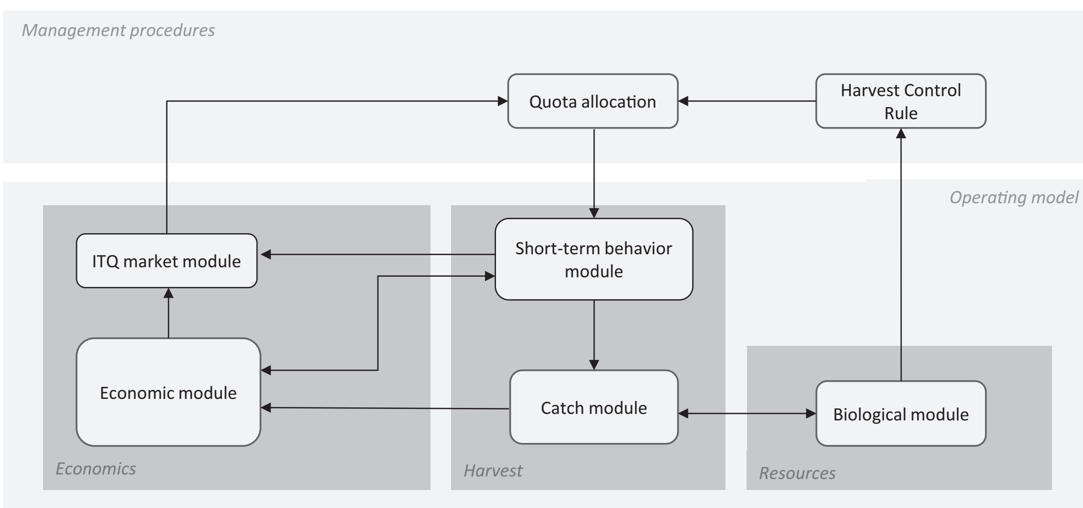

Figure 3. Flow chart of the IAM model. Details of the different modules can be found in Supplementary Material B.

referred to Supplementary Material B for a complete description of the modules already present in Briton *et al.* (2019). As represented in Figure 3, the dynamics of the stocks are modelled in the *biological module* (Supplementary Material B.1) with catch information from the *catch module* (Supplementary Material B.5). Stock dynamics include age-based, age- and sex-based (Methot and Wetzel, 2013), or global surplus production (Fox, 1970) models. The stock abundance calculated by the biological module is used to set the following year's TACs in the *Harvest Control Rule module* (Supplementary Material B.2). Quotas are then allocated to individual operators who can decide to lease in/out quota as modelled in the *ITQ market module* (Supplementary Material B.3). The ITQ market module relies on an iterative algorithm mimicking Walrassian "tâtonnement" to establish equilibrium lease prices of quota units in perfectly competing markets (Walras and Dockès, 1988). The model captures core properties of ITQ markets, such as the allocation of quotas to the most efficient vessels, but also some specifically emerging in multispecies fisheries, such as the economic incentive to redirect fishing effort towards more catch of species with low demand on the quota market (i.e. species with TACs in excess; Holland and Herrera, 2006). The term "tâtonnement" (French for "trial and error") refers to the mechanism by which lease prices of quotas are iteratively adjusted towards their clearing value, i.e. that at which demand for quota (expected landings) equals supply (the TAC). This is done by increasing (resp. decreasing) prices when demand exceeds (resp. is below) supply. As a consequence, the equilibrium lease price of quota in excess is null, and that of binding species (i.e. those for which the TAC is entirely caught) reflects the shadow value of the joint catch. Described formally, the iterative algorithm progresses as follows:

For each iteration, *it* of the tâtonnement process:

(1) Individual harvesters make fishing plans.

- Effort allocation among metiers is modelled as a function of a weighted average of the metiers' expected profitability and past effort allocation. This model is similar to that from Andersen et al. (2010), but without the parameter estimation, as in Marchal *et al.* (2011). The expected profitability of metier m for individual harvester i at time t and iteration it ($ProfPUE^*_{i,m,t,it}$) is calculated as follows:

$$ProfPUE^*_{i,m,t,it} = (1 - cshr_i) \times \sum_s \left(\frac{L_{s,i,m,t-1}}{E_{i,m,t-1}} \times p_{s,t-1}\right) - \sum_s \left(\frac{L_{s,i,m,t-1}}{E_{i,m,t-1}} \times \tilde{qp}_{s,t,it}\right) - CvarUE_{i,m,t-1} - \frac{Cfix_i + Cdep_i + Copport_i}{E_{i,t-1}}, \quad (1)$$

$cshr_i$ represents the crew share of individual harvester i, $\frac{L_{s,i,m,t-1}}{E_{i,m,t-1}}$ the previous year's landings per unit of effort of species s by individual i in metier m, $p_{s,t-1}$ the ex-vessel price of species s in the previous year, and $\tilde{qp}_{s,t,it}$ its lease price in the current iteration. $CvarUE_{i,m,t-1}$ represents the variable costs per unit of effort in the previous year for individual i in metier m, and $\frac{Cfix_i+Cdep_i+Copport_i}{E_{i,t-1}}$ the vessel's fixed and capital costs per unit of effort. Relative profitabilities $ProfPUE^*_c$ (i.e. centred on the profitability of the vessel's least profitable metier) are used in the effort allocation function to avoid negative coefficients: $ProfPUE^*_{c_{i,m,t,it}} = ProfPUE^*_{i,m,t,it} - \min_m(ProfPUE^*_{i,m,t,it})$

The proportion of effort individual harvester i plans to allocate to metier m at time t and iteration it ($pE^*_{i,m,t,it}$) is calculated as follows:

$$pE^*_{i,m,t,it} = \alpha \times \frac{ProfPUE^*_{c_{i,m,t,it}}}{\sum_m ProfPUE^*_{c_{i,m,t,it}}} + (1-\alpha) \times \frac{E_{0_{i,m}}}{\sum_m E_{0_{i,m}}}, \quad (2)$$

with $E_{0_{i,m}}$ being the historical effort of individual harvester i allocated to metier m and α the weight given to profitability in the allocation of effort. When $\alpha = 0$, individuals are assumed to operate according to past habits, whereas when $\alpha = 1$, effort allocation is entirely profit-driven. In the latter case, effort allocation notably responds to economic incentives emerging from quota markets and fishing effort is primarily directed towards metiers catching greater proportions of species with low demand on the quota market.

- Given the planned allocation of fishing effort, individual harvester i assesses whether it is profitable to go fishing. If the average profitability per unit of effort, $ProfPUE^*_{i,t,it} = \sum_m (pE^*_{i,m,t,it} \times ProfPUE^*_{i,m,t,it})$, is positive, then individual harvester i will plan to operate in the fishery with a level of fishing effort limited by a maximum effort E_{max_i} (E_{max_i} is set based on empirical information available regarding the maximum levels of fishing effort per vessel observed in the fishery). Otherwise, he plans to remain in port:

$$E^*_{i,t,it} = \begin{cases} E_{max_i} & \text{if } ProfPUE^*_{i,t,it} > 0, \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

This means that only profitable vessels plan to be active in the fishery.

(2) The biological and catch modules are called to estimate individual demands for quotas (i.e. expected landings $L^*_{i,s,t,it}$) given fishing plans in the current iteration.

(3) Finally, quota prices are adjusted for the next iteration for each species, until quota lease markets clear (the tâtonnement process):

$$\tilde{qp}_{s,t,it+1} = \tilde{qp}_{s,t,it} \times \left(1 - \lambda_q \times \frac{TAC_{s,t} - \sum_i L^*_{s,i,t,it}}{TAC_{s,t}}\right), \quad (4)$$

with $TAC_{s,t}$ being the TAC for species s at time t and λ_q a fixed multiplier. The value of the multiplier is determined empirically to achieve a satisfying compromise between the precision of convergence and computing time. Precision will be greater for low values of λ but at the cost of increased convergence time.

Steps 1–3 are iterated until total demand for quota is close enough to the TAC for all species (i.e. $\frac{TAC_{s,t} - \sum_i L^*_{s,i,t,it}}{TAC_{s,t}} < \epsilon$) or after it_{max} iterations. Let us denote it_e the iteration at which the iterative process stops.

(4) Quota prices are set at their equilibrium value ($qp_{s,t} = \tilde{qp}_{s,t,it_e}$) and quotas for all species are traded. Individual net demands for quota ($Demand$) are calculated by deducing expected catches at equilibrium (L^*) from initial quota holdings ($Holdings$):

$$Demand_{s,i,t} = Holdings_{s,i,t} - L^*_{s,i,t,it_e}. \quad (5)$$

Similar to the approach proposed by Little *et al.* (2009), priority is given to trades between participants with the highest incentive to lease out or to rent quota. The incentive to take part in a trade is measured by $|ProfPUE^*_{i,t,it_e}|$. For each species, quota leasers are ranked by decreasing order of profitability and quota lessors by increasing order of profitability. Trades are conducted by order of priority under the limit of what is available or needed, i.e. $\min(-Demand_{s,lessor}, Demand_{s,leaser})$, and so until offer or demand expires. Some quota may also be held by external investors, which are grouped into an additional market participant.

This reallocation of quota then constrains individual fishing efforts in the *short-term behaviour module* (Supplementary Material B.4). The short-term behaviour module calculates fishing efforts at the vessel and metier level as the result of two processes: (i) the allocation of effort among metiers at the individual level and (ii) the determination of individual annual efforts. Effort allocation among metiers is modelled as in the ITQ market module (Equation 2) and therefore corresponds to that obtained at equilibrium of the tâtonnement process: $pE_{i,m,t} = pE^*_{i,m,t,it_e}$. As in Briton *et al.* (2019), annual fishing efforts $E_{i,t}$ are set so that individuals stop fishing once they have reached their most constraining quota. Fishing efforts at the individual and metier level are then used to calculate catches and landings in the *catch module*. Finally, the *economic module* calculates a variety of economic indicators at the individual and metier level. This work gives particular attention to the following:

- the number of active vessels Nbv_t in the sub-fishery at time t, i.e. the number of vessels landing at least one species in the species pair, and which remained active in the fishery (as this was profitable) after the trading of quota:

$$Nbv_t = \sum_{i \in S_i(sp1,sp2)} \delta_{i,t}, \tag{6}$$

  with $\delta_{i,t} = 1$ if $E_{i,t} > 0$ and 0 otherwise. $S_i(sp1, sp2) = \{i, L_{i,sp1} > 0 \vee L_{i,sp2} > 0\}$ is the set of individuals i in the sub-fishery $(sp1, sp2)$, namely those landing at least one of the two species defining the sub-fishery ($L_{i,sp1} > 0$ or $L_{i,sp2} > 0$).
- the annual tonnage of landings L_t in the sub-fishery, i.e. the annual weight landed (across all species) by individuals and metiers landing at least one species in the species pair:

$$L_t = \sum_{(i,m) \in S_{i,m}(sp1,sp2)} L_{i,m,t}, \tag{7}$$

  with $S_{i,m}(sp1, sp2) = \{(i, m), L_{i,m,sp1} > 0 \vee L_{i,m,sp2} > 0\}$ the set of individuals i and metiers m in the sub-fishery $(sp1, sp2)$,
- the annual total wages of crews $Wage_t$ in the sub-fishery, calculated as a proportion of the revenue from fishing as generally observed in this fishery:

$$Wage_t = \sum_{(i,m) \in S_{i,m}(sp1,sp2)} (cshr_i \times GVL_{i,m,t}), \tag{8}$$

  with $GVL_{i,m,t}$ the gross value of landings of individual i in metier m at time t and $cshr_i$ the share of the revenue of individual i distributed to its crew.
- and the annual Net Economic Returns NER_t of the sub-fishery:

$$NER_t = \sum_{(i,m) \in S_{i,m}(sp1,sp2)} NOS_{i,m,t}, \tag{9}$$

  with $NOS_{i,m,t}$ the net operating surplus of individual i, metier m at time t:

$$NOS_{i,m,t} = (1 - cshr_i) \times GVL_{i,m,t} - Cvar_{i,m,t} - (Cfix_i + Cdep_i) \times \frac{E_{i,m,t}}{E_{i,t}}, \tag{10}$$

  with $Cvar_{i,m,t}$ the variable costs of individual i in metier m at time t and $Cfix_i$ and $Cdep_i$ the fixed and depreciation costs of individual i. The latter two are allocated to metier m based on its share in fishing effort $\frac{E_{i,m,t}}{E_{i,t}}$.

These four indicators are used to quantify the socio-economic performance of the fishery. The number of active vessels proxies employment levels, net economic returns measure the surplus of capital owners, and wages measure the surplus of crew members. The sub-fishery's landings are considered a proxy for economic activity in the post-harvest sectors (e.g. auction halls, processing plants, fishmongers; Dyck and Sumaila, 2010) as the more fish is landed, the more people are required to process and sell the product. The amount of fish landed also directly affects food supply and therefore has implications for the wider society.

Model calibration

Biological parameters

The SESSF Harvest Strategy uses a tier-based approach conditional on data availability to assess stock status and recommend catch levels (Dowling *et al.*, 2016; AFMA, 2017). Tier 1 assessments provide the highest quality assessments based on the estimation of age- and occasionally sex-based population dynamics. Outputs from those assessments were used to calibrate the dynamics of the Tier 1 stocks in IAM. The previous Tier 2 analysis, which applied to stocks that have a less robust quantitative assessment, is no longer being used. Tiers 3 and 4 simply use indicators such as fishing mortality and catch rates to estimate stock status, without a population dynamics model being fitted to data. Consequently, commercially important stocks in those tiers were modelled with a surplus production model, the parameters of which were either retrieved from Pascoe *et al.* (2018) or specifically estimated for this work. Overall, 16 stocks were dynamically modelled [i.e. with either an (sex- and) age-based or surplus production model], accounting for 75% of the fishery's value in 2015, 4 with age-based dynamics, 6 with age- and sex-based dynamics, and 6 with a surplus production model (Supplementary Material Table C.1). Biological parameters are provided in Supplementary Material Table C.2. Landings of the remaining stocks (also referred to as "static" stocks) were calculated assuming constant landings per unit of effort.

Annual stock–recruitment was modelled using a Beverton–Holt stock–recruitment relationship with parameters specified in Supplementary Material Table C.2. Uncertainties in the stock–recruitment relationship of the stocks were modelled as deviations from the stock–recruitment relationship. Formally, the observed recruitment $N_{0,t}$ was calculated as:

$$N_{0,t} = \frac{4hR_0 SSB_t}{SSB_0(1-h) + SSB_t(5h-1)} e^{\tilde{R}_t - \frac{\sigma_R^2}{2}} \quad \tilde{R}_t \sim N(\mu_R; \sigma_R^2) \tag{11}$$

with h the steepness parameter, R_0 the unfished equilibrium recruitment, SSB_0 the unfished equilibrium spawning biomass, and R_t the deviation from the recruitment relationship drawn from a normal distribution of mean μ_R (representing recruitment shifts) and standard deviation σ_R^2. Bias in the estimation of the mean associated with the lognormal distribution is corrected by subtracting the factor $\frac{\sigma_R^2}{2}$ in the exponent (Methot and Taylor, 2011).

Stock-specific reference points were also calculated from stock assessment outputs: F_{MSY} the fishing mortality rate maximizing yield at equilibrium and F_{20} the fishing mortality rate associated with an equilibrium biomass equal to 20% of its virgin value. The

Table 2. List of fleets and metiers for the Southern and Eastern Scalefish and Shark Fishery.

Sector	Fleets	Metiers	
		Gear	Target species/assemblage
CTS	Shelf trawlers East	Trawl East	Flathead
	Mixed trawlers East		Pink ling
	Royal red prawn trawlers		Royal red prawn
			Orange roughy
			Jackass Morwong
			Squids
			Frostfish
			Ocean jackets
			Mixed shelf
			Mixed slope
	Mixed trawlers West	Trawl West	Blue grenadier
	Blue grenadier trawlers		Pink ling
			Squids
			Mixed deepwater
			Mixed shelf
			Mixed slope
	Flathead Danish seiners	Danish seine	Flathead
	School whiting Danish seiners		School Whiting
			Mixed
GHTS	Gillnetters	Gillnet	Gummy shark
			Mixed
	Shark bottomliners	Bottomline	Gummy shark
	Mixed bottomliners		Blue-eye trevalla
			Mixed scalefish
	Blue-eye dropliners	Dropline	Blue-eye trevalla
			Gummy shark
			Mixed scalefish
	Blue-eye auto-longliners	Automatic longline	Blue-eye trevalla
	Mixed auto-longliners		Pink ling
			Mixed scalefish

latter is the limit reference point specified by default in the Commonwealth Harvest Strategy Policy (Department of Agriculture and Water Resources, 2018). Details about the calculation of both reference points are provided in Supplementary Material C.1.

Fleet and metier characterization

Multivariate clustering analyses of the species composition of the value of landed catch at the haul level were carried out to define metiers in the fishery. These analyses followed the workflow developed by Deporte *et al.* (2012) to define metiers in European fisheries. Landed catch at the haul level was retrieved from the fishery's logbooks, and fish prices from Mobsby (2018). Only fishing seasons from 2012 to 2017 were considered in order to provide a recent description of fishing activity in the fishery. An important underlying assumption of output-based approaches to defining units of fisher behaviour is that the outcome from fishing reflects the original fishing attention. Yet, due to the uncertain nature of catch composition in mixed fisheries, realized catch might not match that intended. In order for identified metiers to effectively capture fishing intentions, further refinement of the groups obtained with the clustering algorithm was carried out. This post hoc treatment consisted of assigning all clusters for which the main species in value was not identified as a targeted species by industry members to a "mixed" metier. The same methodology, but this time based on the vessels' effort allocation among metiers, was used to define fleets within sectors. Details about these analyses are provided in Supplementary Material A. A total number of 13 fleets and 30 metiers were identified in the fishery and given in Table 2. Figure 4 illustrates fishing strategies across fleets by showing how they allocate their fishing effort among metiers that aim at targeting specific (assemblages of) species. Fleets are not used *per se* in the model since vessels are represented individually, but are used to aggregate and present model outputs at a meaningful scale. Landings and fishing days were aggregated at the vessel and metier level to calibrate the model.

Economic parameters

Ex-vessel price for the various species in 2015 was obtained from Australian Fisheries Statistics (Mobsby, 2018). Cost structures were estimated at the fleet level based on the economic survey carried out in 2015 (Bath *et al.*, 2018) and personal communications from ABARES, and details about the economic calibration are given in Supplementary Material C.5. The maximal annual fishing effort of individual i (E_{max_i}) was assumed to be its maximal observed effort over the period 2010–2015.

The model endogenously determines equilibrium quota lease prices only for the species explicitly under TAC management in the simulated scenario. As described in "Exploring flexibility in joint productions" section, we looked at the joint management of pairs of species, with the control of the catch of other species not being explicitly represented in the model. When fishers are

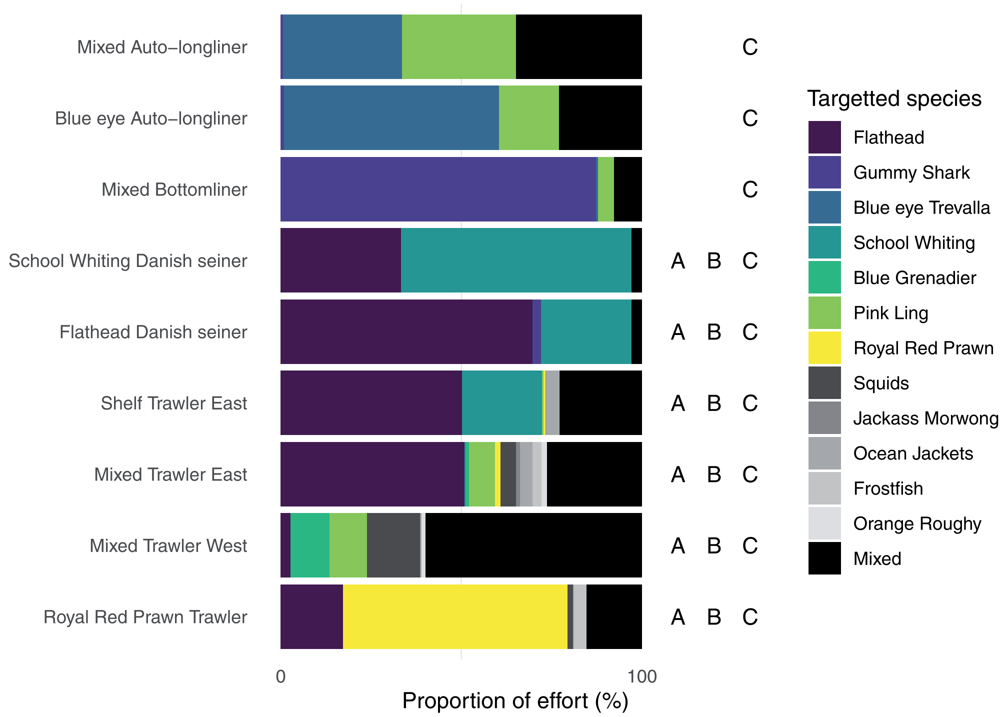

Figure 4. Effort associated with metiers aiming at targeting various species by fleet in the SESSF. Primary target species are represented in colour scale, secondary target species in greyscale and black colouring refers to fishing effort allocated to "mixed" metiers, i.e. without a particular target species identified. The sub-fisheries (A: Flathead—John Dory, B: Flathead—Jackass Morwong, and C: Flathead—Pink Ling) in which each fleet operates are indicated right to the plot. Taxa names for the different species can be found in Supplementary Material C.1. *Source:* Logbook data aggregated by fleet and metier as defined in Supplementary Material A.

assumed to allocate fishing effort based on the expected profitability of the metiers they practise (i.e. $\alpha > 0$ in Equation 2), fishing effort tends to shift towards metiers catching more of the unregulated species because of the lower quota costs associated with their operation. In order to avoid unrealistic effort shifts towards species not explicitly under TAC management in the simulated scenarios, we exogenously set non-null quota lease prices for the latter. This was done using data on quota lease prices collected by the Australian Fisheries Management Authority since July 2017 (Supplementary Material C.3). Finally, in the absence of information on quota ownership, we assumed that quotas were owned by investors not participating in the operation of the fishery. This assumption does not change how quota is finally allocated since the opportunity cost of leasing in/out quota does not depend on quota holdings, but it affects the distribution of profits (in this case, the rent associated with holding quotas is not perceived by fishery operators).

Exploring flexibility in joint productions

For each sub-fishery described in "The SESSF" section, we compared achievable harvest rates under two fishing behaviour scenarios: habit- ($\alpha = 0$ in Equation 2) and profit-driven ($\alpha = 1$) effort allocation. To do so, we simulated a set of combinations of fishing mortality targets used in the HCR to set annual TACs for the two species of interest. For each sub-fishery and value of α, the ensemble of simulated scenarios thus takes the form of a bi-dimensional grid consisting of 10×10 pairs of fishing mortality targets. Each tile in the results figures corresponds to a simulated scenario (i.e. a pair of fishing mortality targets). Each scenario was run over a 10-year projection period starting from the most recent year the model could be calibrated upon (2015) and across 100 replicates to account for uncertainties related to stock recruitment (Equation 11). The HCR simply calculates annual TACs by applying a fishing mortality target $\overline{F}_{targ}$ to the current stock abundance (Supplementary Material B.2). As in Briton *et al.* (2019), we identified the operating domain, defined as the subset of fishing mortality target combinations allowing the landings of both stocks to be at least 90% of TAC.

In addition to identifying the operating domain, we also calculated average performance indicators for the sub-fishery of interest, namely $\overline{Nbv}$, $\overline{L}$, $\overline{Wages}$ and $\overline{NER}$, respectively, being the average through time and across replicates of Nbv_t, L_t, $Wages_t$, and NOS_t defined in "IAM bio-economic model" section.

Results

Flexibility in joint productions

We first consider the operating domains (i.e. sets of achievable fishing mortality targets) obtained assuming a habit-driven effort allocation ($\alpha = 0$). We can note a gradual increase in these domains' areas from sub-fishery A (Figure 5a) to sub-fishery B (Figure 5b) and sub-fishery B to sub-fishery C (Figure 5c), with the latter increase being somewhat larger. When effort allocation among metiers is fixed to that in the reference year, the ratio in which both species are caught is constrained to that in the reference year if all vessels catch both species at the annual level (even if not at the metier level). Such a situation results in a linear

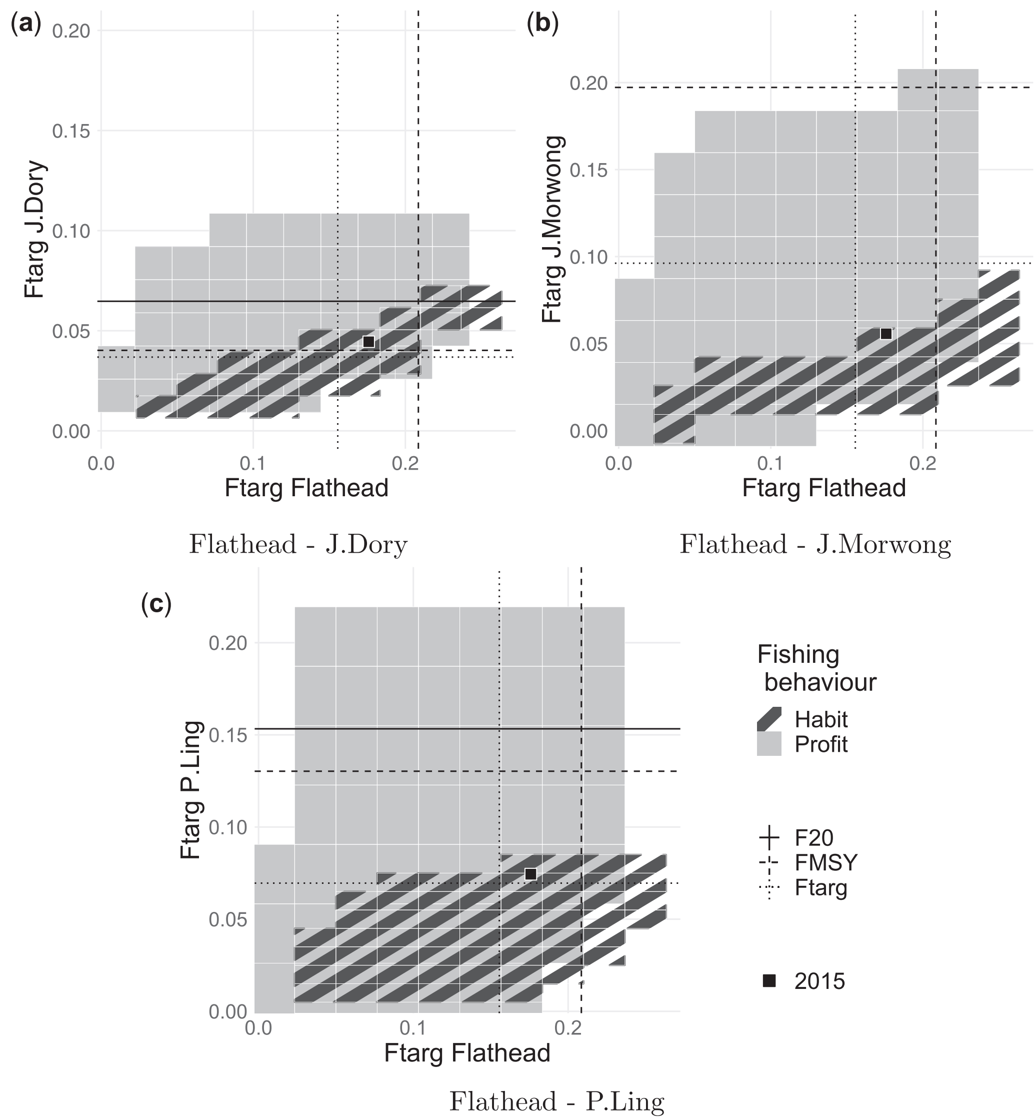

Figure 5. Operating domains for three pairs of species (Flathead—John Dory, Flathead—Jackass Morwong and Flathead—Pink Ling) under two scenarios of fishing effort allocation: habit- ($\alpha = 0$) and profit-driven ($\alpha = 1$). (a) Flathead—J. Dory, (b) Flathead—J. Morwong, (c) Flathead—P. Ling. The operating domain refers to the set of fishing mortality target combinations that allow at least 90% of the TACs of both species to be caught. Simulated values correspond to the centre of the tiles, and are specific to each sub-fishery and fishing scenario in order to optimize the graphs' resolution. Black squares show fishing mortality rates in the reference year (2015), dotted lines current management targets formulated in terms of fishing mortality rates, dashed lines singles-species F_{MSY} reference points, and solid lines (when within the operating domain) F_{20} limit reference points.
Source: Output from IAM model.

operating domain like those in Figure 5a and b (The operating domains associated to the habit-driven scenario in Figure 5a and b are not perfectly linear because they correspond to the area where at least 90% of both TACs is caught. Increasing the percentage of TAC uptake used to define the operating domain would narrow these operating domains towards their linear limit under TAC uptake requirements of 100%. Yet, because of the discrete nature of the simulation grid, it was not possible to increase this uptake rate while maintaining continuous operating domains). A wider operating domain in the habit-driven scenario indicates that there are vessels in the fishery that only catch one of the two species, hence that is not constrained by the TAC of the other species. This is the case in sub-fishery C as longliners only operate on the continental slope, targeting species such as pink ling or blue-eye trevalla, and therefore not catching flathead present at shallower depths. This situation requires that both species can be fished independently, i.e. by different metiers, but also that some fleets only participate in one of the two fisheries for economic (not competitive with other fleets), operational (unsuitable gear), or regulatory (exclusion from fishing grounds) reasons.

Expansion of the operating domain under profit-driven effort allocation shows that there is flexibility in achievable catch compositions in all three cases. Whereas this could be easily intuited for sub-fishery C, since flathead and pink ling are caught by different metiers operating at different depths, such flexibility seems more surprising for species that share the same habitat such as flathead, john dory (A) and jackass morwong (B). In the latter cases, fishers have nevertheless the possibility to alter the ratios in which they catch co-occurring species by fishing in different areas or at different times within the same habitat. In this case, the greater the targetability of each species, the greater the flexibility in achievable catch ratios. Indeed, whereas both the ratios of john dory and jackass morwong to flathead can increase when switching effort from metiers targeting flathead to more mixed metiers, that of jackass morwong to flathead can also increase when more fishing effort is allocated to targeting jackass morwong. As a result, there is more room for manoeuvre in the latter case, illustrated by a greater expansion of the operating domain in Figure 5b than in Figure 5a when allowing for effort shifts between metiers.

Figure 5 shows that, retrospectively, flathead and pink ling were harvested slightly above their target in 2015, and jackass morwong harvested well below (Stock assessments used in the present study were carried out in 2016 for flathead and 2018 for pink ling and jackass morwong. These assessments indicate "retrospective overfishing" of flathead and pink ling in 2015, despite their TACs not having been fully caught that year). Although Figure 5 shows that john dory was harvested above its target, which was calculated using a global surplus production model, in reality, the TAC was set at a higher level, based on an empirical HCR (Little *et al.*, 2011), and so did not choke the fishery.

Our simulations show that current management targets (dotted lines) for flathead, john dory, and pink ling are achievable under current fishing practices since they lie within habit-based (striped) operating domains. However, reaching that of jackass morwong is only possible provided changes in the allocation of effort among metiers, as illustrated by target reference points in Figure 5b being within the profit-driven operating domain (grey). Changes in fishing practices can also bring single-species F_{MSY} reference points (dashed lines) within the set of achievable targets. This is, for instance, the case of jackass morwong and pink ling, potentially harvested at MSY in the profit-driven effort allocation scenario (Figure 5b and 5c). In the three cases studied here, changes in fishing practices lean towards higher harvest rates of john dory, jackass morwong, and pink ling relative to flathead, as illustrated by operating domains extending towards the upper part of quadrant in Figure 5. This is a consequence of most of the fishing effort of the fleets catching flathead (mainly trawlers

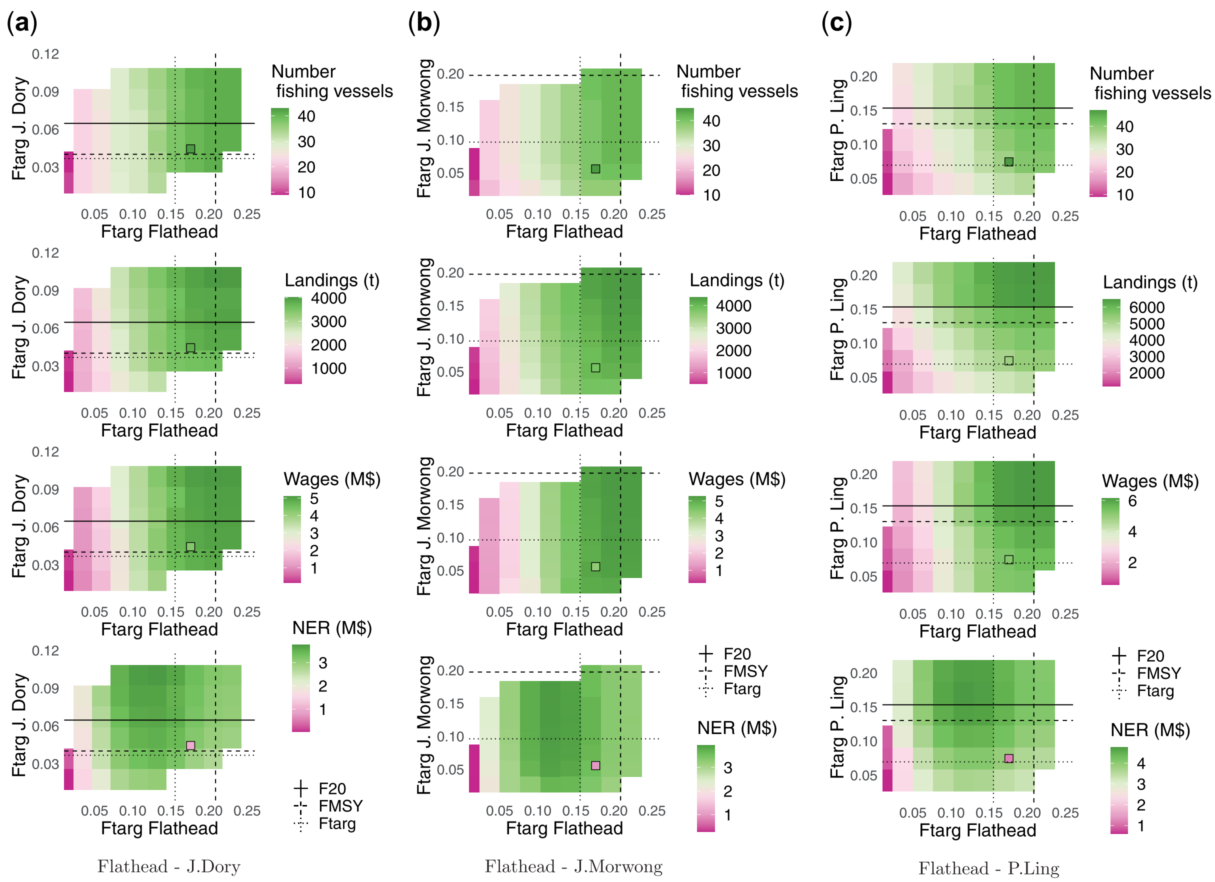

Figure 6. Fishery indicators in the profit-driven ($\alpha = 1$) fishing behaviour scenario for the three sub-fisheries. (a) Flathead—J.Dory, (b) Flathead—J. Morwong. From top to bottom: the number of active vessels in the sub-fishery, and the sub-fishery's landings, total crew wages, and net economic returns (NER) averaged over the 10-year simulation period and across replicates. Filled squares show fishing mortality rates in the reference year, with the colour of the filling indicating the value of the indicator in the reference year. Dotted lines current management targets formulated in terms of fishing mortality rates, dashed lines singles-species F_{MSY} reference points, and solid lines (when within the operating domain) F_{20} limit reference points.
Source: Output from IAM model.

and Danish seiners in the east) currently being dedicated to targeting flathead (Figure 4), hence constituting a significant amount of effort that can potentially shift towards metiers catching more of the other species (john dory, jackass morwong, and pink ling) such as mixed metiers or specific targeting these species.

Socio-economic performance

Figure 6 presents the socio-economic implications of choosing specific management targets within the achievable set under the profit-driven fishing behaviour scenario. We specifically show the number of active (profitable) vessels in the sub-fishery as well as the sub-fishery's landed weight, total wages, and net economic returns averaged over the 10-year projection period and across replicates.

Varying patterns are evident between sub-fisheries A (Figure 6a) and B (Figure 6b) on the one hand and sub-fishery C (Figure 6a) on the other hand. Indeed, socio-economic indicators for sub-fisheries A and B are mostly driven by the fishing mortality target chosen for flathead, which is the key economic species of both sub-fisheries. This is illustrated by quasi vertical isolines for most indicators in Figure 6a and b, meaning that for a given harvest rate for flathead, the choice of the management target for either jackass morwong (B) or john dory (A) makes little difference to the fishery's socio-economic performance. One can also see that in these two sub-fisheries, the number of active vessels as well as the sub-fishery's landings and crew wages are maximized under the highest harvest rates of flathead. Net economic returns, however, are maximized under lower harvest rates, a well-known result in fisheries economics (Gordon, 1954).

Projection results can also be compared to the value of the four indicators in the reference year, the latter being indicated by the colour of the reference square filling. One can, for instance, see that fewer vessels (if operating at their full capacity Eff_{max}) could be used to harvest the stocks at their 2015 level. In all three cases, sub-fisheries NERs expected under similar harvest rates increase relative to the reference situation. This highlights a currently sub-optimal allocation of quota among vessels and effort among metiers.

On the contrary, the performance of sub-fishery C is clearly dependent on the targets imposed on both species as shown by Figure 6a. This is a consequence of both flathead and pink ling being economically important for the fishery. Similarly to sub-fisheries A and B, the number of active vessels, total landings, and wages in sub-fishery C are maximized at the highest harvest rates of both species, whereas the maximum of NER is reached under lower harvest rates of both species.

The indicator values displayed in Figure 6 are 10-year averages starting from the reference year and not long-term equilibria. This partly explains why sub-fishery's landings can be maximized under higher fishing mortality rates than the equilibrium F_{MSY} reference points. Another reason for landings to be maximized under fishing mortality rates higher than the single-species reference points is that landings presented here are not only those of the two species of focus but those of all the jointly caught species. As most secondary species in the SESSF currently have catches and fishing mortalities below that which would deliver MSY, achieving overall MSY in the SESSF inevitably leads to harvesting some key stocks above their individual MSY, and sometimes above their limit reference point F_{20}. Moreover, current targets do not allow sub-fishery-wide NERs to be maximized. Precisely, current targets are, respectively, expected to generate 87%, 96%, and 84% of the potential maximal NER (on average over the 10-year period) in sub-fisheries A, B, and C.

Discussion

Our simulations show that there is significant flexibility in terms of achievable relative harvest rates in the SESSF. Interestingly, such flexibility is not only observed for species that can be caught independently from each other, but also for species that spatially co-occur. The extent to which changes in fishing practices can help expand the space of achievable catch compositions in the latter case is constrained by the possibility for fishers to increase or decrease the proportion in which they catch the different species by fishing in different areas or at different times within the same habitat. Such a short-term strategy to explore the space of achievable catch compositions can be contrasted to a longer-term and potentially costlier strategy of experimenting with gear changes.

These results seem particularly relevant for the scientific community providing TAC advice for mixed fisheries. In Europe, for example, the ICES Working Group on Mixed Fisheries Advice (WGMIXFISH-Advice) provides the European Commission with alternative harvest rates within ranges around MSY so that TACs can better match the ratios in which individual species are currently caught (ICES, 2017; Ulrich *et al.*, 2017). By doing so, ICES has taken the path of accommodating management objectives to current fishing practices. However, this work shows that there is also room for fishing practices to adapt to the regulation, and that assumptions of purely joint production may indeed not constitute a fully adequate underpinning for mixed fisheries TAC advice. Our simulations show that in the SESSF, changes in fishing practices, incentivized by well-functioning quota markets, could allow single-species targets to be met, despite existing technical interactions. Although this result may not be encountered in all mixed fisheries contexts, it suggests a need for in-depth examination of the mechanisms shaping joint production in these fisheries, and the extent to which they provide for at least some flexibility. Indeed, approaches supporting the management of mixed fisheries are likely to lie between traditional single-species approaches, simply ignoring mixed fisheries interactions, and those assuming that species are caught in absolutely fixed proportions.

Although our simulations suggest that catch composition in the SESSF is quite flexible, we would argue that the light grey operating domains in Figure 5 provide a rather optimistic estimation of such flexibility. First, the domains result from fishers only allocating their effort based on the profitability of the metiers. Yet, the allocation of effort between metiers can be constrained by factors not accounted for in the present work, such as their operation being restricted to particular seasons or to fishing grounds that are not always accessible. Such constraints, and the scale at which they operate to restrain flexibility in fishing operations, may not be easily observable and systematically quantifiable at the level of individual operations. The metier analysis carried out as part of this work did not evidence clear seasonality in the considered metiers. If it were to be the case, exogenous constraints on the effort allocated to each metier could be imposed in the model to reflect known constraints pertaining to non-modelled processes (e.g. the time at sea allocated to a seasonal metier not exceeding the known length of the season). Effort re-allocation is also likely to be limited by quota constraints not accounted for in the simulations presented in this study. Indeed, in each case study, only the two species defining the sub-fishery have a formal TAC constraint, which does not prevent other stocks in the fishery from being overfished, as discussed in more detail in Supplementary Material D. This could be addressed by increasing the number of TAC constraints jointly considered in the simulations. Furthermore, the modelled operating domains result from perfectly functioning quota markets where all lessees find a leaser at equilibrium. However, frictions in quota markets caused by operators trading quotas in a context of uncertainty in what will be caught and without perfect information on quota supply and demand can limit the malleability of fishing practices (Innes *et al.*, 2014a; Ropicki and Larkin, 2014).

In addition to constraints limiting fishers' control over catch composition, incentives could also be lacking to adjust catches to quota availability. Limited demand for some species on the market could for instance lead fishers to limit their catch of the latter. Such demand limitations may interact with seasonal and spatial patterns in the accessibility of the different species available to the fishers, leading to limited incentives to target certain species at certain times of the year. This limitation could be addressed by incorporating market dynamics in the model. Moreover, the modelled operating domains result from quota markets operating at competitive equilibrium, where quota lease prices track quota availability, thus providing the economic incentives to avoid catching species with constraining TACs. Yet, recent data on lease markets in the SESSF show that such incentives may not manifest themselves fully in the fishery, as quota lease prices do not always match those expected under market equilibrium. Indeed, as observed in other multi-species fisheries quota markets (Holland, 2013; Hatcher, 2014; Innes *et al.*, 2014b), cases of non-binding quotas being traded at positive prices, and of prices of binding quotas being capped, are encountered, quota lease prices thus not fully expressing their implicit values. Finally, one may also need to relax the assumption that fishing choices can be modelled considering perfect information of fishing operators regarding the nature of the constraints and trade-offs associated with alternative choices, and individual profit-maximizing behaviour. Further developments in this domain could consider for example the role of social networks in information sharing or of social–psychological factors in explaining observed fishing behaviour in real-life fisheries (van Putten *et al.*, 2012).

Constraints, limited incentives, and behavioural drivers may all contribute to what is often considered to be a perpetuation of fishing habits observed in many fisheries worldwide (Holland and Sutinen, 1999; Hutton *et al.*, 2004; Marchal *et al.*, 2009, 2013; Girardin *et al.*, 2017). These could be accounted for by specifically estimating the parameter α driving fishing dynamics in the fishery, as done by Marchal *et al.* (2013) for the French deepwater trawlers in the North Sea. However, such estimations based on past realizations may be limited in their ability to capture the full potential of a fishery's adaptability. Another way to explore possible futures of a fishery, while acknowledging that fishers tend to adhere to habits for reasons that are difficult to capture in a model, would be to consider the cases $\alpha = 0$ and $\alpha = 1$ as bounding scenarios for its likely evolution.

Estimating the flexibility in achievable catch compositions also requires a good understanding of the production technology, without under- nor over-estimating the control fishers have over their catch composition. When defining metiers based on statistical analyses of the fishing output (as done in the present study), one faces the risk of missing existing fishing activities if they have only rarely been exerted by fishers over the considered time period. One also faces the risk of over-estimating fisher control over the catch composition if a diversity in this composition is the result of environmental variability rather than targeting efforts. Collecting information on fishing intentions [as done for instance in the South Australian Marine Scalefish Fishery (Steer *et al.*, 2018), or partially in French fisheries in monthly activity calendars (Demanèche *et al.*, 2016)] could therefore considerably facilitate the definition of metiers. Yet, in the absence of such information, both risks can be mitigated by calling on industry professionals to complement or reduce the set of clusters produced by statistical methods to identify metiers that adequately capture the diversity of fishing practices in mixed fisheries. In our case, we addressed this issue by soliciting fishermen's expertise to filter out statistical clusters that did not match targeting intention, and merge them into a "mixed" metier.

The spatio-temporal resolution at which catch data is available can also prevent an adequate determination of joint productions since catch composition can be the result of spatially and temporally fine-scale decisions (Mateo *et al.*, 2017; Dépalle *et al.*, 2021). However, we do not believe it to be the case here as our clustering analysis was applied to catch data at the haul level. Finally, mixed fisheries being very dynamic systems, where fishing strategies regularly evolve in response to species availability, market demand, or management regulations, it is important to regularly update analyses aiming at defining fishing strategies and their resulting catch. This would call for an institutional set-up for the drafting of advice that incorporates regular re-assessment of the structure of metiers in a fishery, involving expert input from the fishing industry.

Given a potentially important part of joint productions in fisheries is determined by fishers' choices [as suggested by this work but also highlighted by many prior empirical studies such as Branch and Hilborn (2008), Abbott *et al.* (2015), or Little *et al.* (2015)], we can only emphasize the need to pursue research aiming at better understanding fishing behaviour in mixed fisheries (including drivers as well as limitations), but also to start using this knowledge to advise on the management of those fisheries through its implementation in decision-support modelling frameworks. In this regard, we support the conclusion drawn by Ulrich *et al.* (2011) that both metier and operator entities should be represented in integrated models of mixed fisheries since they, respectively, materialize the technical and behavioural determinants of joint productions. Whereas omitting the metier level is likely to under-estimate the flexibility in catch composition resulting from changes in fishing practices, representing a fishery as a set of independent metiers without accounting for their joint operation by individual operators is likely to over-estimate that same flexibility.

This work also shows a hierarchy among species in the SESSF, with the harvest targets imposed on the primary commercial species determining most of the fishery's production, employment, and economic surplus. Secondary species only have a marginal influence on the overall performance of the fishery. This has practical implications for management as it justifies setting targets that align with socio-economic management objectives for the primary commercial species first. Secondary species could be managed with respect to ecological objectives mainly, with catch limits being capped by a limit reference point pertaining to stock conservation or wider ecological objectives. The extent to which these conclusions, drawn for the SESSF, could extend to other mixed fisheries based on a few key commercial species and a suite of secondary species, would require testing.

Conclusion

This work advances the on-going development of management approaches specifically addressing the complexities faced in mixed fisheries. In particular, our simulations suggest that mixed fisheries are likely to feature an important latent flexibility in their catch composition, and that changes in fishing practices can broaden the space of achievable outcomes. In particular, we highlight that well-functioning ITQ markets provide the economic incentive to adjust fishing practices to quota availability. Accounting for the behavioural determinants of joint productions is therefore critical to the provision of relevant TAC advice in mixed fisheries. Moreover, our results suggest that a hierarchical approach to management may be appropriate for mixed fisheries, with target reference points meeting socio-economic objectives being set for the key commercial species, and secondary species being managed so as to steer clear of ecological limit reference points.

Acknowledgements

The authors would like to thank the Australian Fisheries Management Authority for providing access to logbook and SFR trading data as well as stock assessment outputs. We are also grateful to Malcolm Haddon, Jemery Day, and Paul Burch (CSIRO) for their help with the biological calibration of the model and Sean Pascoe (CSIRO) for his help with the economic calibration. We would also like to thank the members of the fishing industry who helped define metiers for the fishery. Finally, we are very grateful to the three anonymous reviewers who provided constructive comments on earlier versions of the manuscript.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article and its Supplementary Materials.

Funding

This work was supported by the University of Tasmania (UTAS)/ Commonwealth Scientific and Industrial Research Organisation (CSIRO) PhD Program in Quantitative Marine Science, a CSIRO ResearchPlus Postgraduate Top-up Scholarship, the French Research Institute for Exploitation of the Sea (Ifremer), the Ecole des Docteurs of University Bretagne Loire, and the Conseil Régional de Bretagne.

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Handling editor: Sarah Kraak