Evaluating effort regulation in mixed fisheries: a Monte Carlo approach

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2019

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Abstract

This paper evaluates whether effort regulation could achieve the goal of protecting low-abundance species in mixed fisheries. We construct a two-species bio-economic model and compare the stock abundance ratio in the end of the fishing season with the ratio prior to the fishing. Fishers' profit maximization problem is governed by three key factors: (a) the overall efficiency of catching different species (catchability), (b) the price of different species, and (c) their ability to catch the favoured species separately from the less-favoured species (separability). Using a Monte Carlo sampling of feasible parameters space, we show that effort regulation has good chances (87% of the cases) of maintaining the end stock ratio near equal levels ($\frac{1}{2} <$ stock ratio < 2) when the initial stock ratio is equal. If the initial stock ratio is not equal, however, there is a high risk (about 50% of the cases) that effort control increases differences in the relative species abundances, rather than diminishing them. The effects depend on whether the key factors determining fishing profitability are counteracting or reinforcing each other, and their relative strength. Our results warn against placing too much faith on the ability of effort regulation to protect species at low abundances from excessive exploitation.

KEYWORDS: mixed fisheries, effort control, bioeconomics modeling, Monte Carlo approach, fisheries management

JEL CODES: Q22, Q57

1 Introduction

Total allowable catch (TAC) regulation, a form of output control, is a single-species management approach that sets stock-specific catch quotas (Stefansson and Rosenberg, 2005). In a mixed fishery where many species are caught simultaneously, management relying on stock-specific TACs can be impractical because of data requirements and costs, and because of discarding of over-quota catches (Daan, 1997; Hilborn et al., 2004; Baudron et al., 2010), or when discarding is not allowed, because species with restrictive quotas (‘choke species’) prevent full utilization of species with more permissive quotas (Kuriyama et al., 2016; Alzorriz et al., 2018; Mortensen et al., 2018). To address these problems, input control regimes, which are often species-unspecific and account for the multitude of species living in an ecosystem, are sometimes favoured for the management of mixed fisheries (Pope, 2002; Squires et al., 2017). Input control regimes set quotas at the operational unit level; for example, quotas are given as total allowable fishing days per fleet category, further split among the individual license holders (Laurec et al., 1991; Andersen et al., 2010; Danielsen and Agnarsson, 2018).

Effort regulation has been practised in many fisheries (Squires et al., 2017), including some Mediterranean fisheries (Vielmini et al., 2017; Mulazzani et al., 2018), the sole and plaice fisheries in the North Sea (European Union Committee, 2008), and the demersal fisheries in Faroese waters (Jákupsstovu et al., 2007; Danielsen and Agnarsson, 2018). Moreover, license control, a dominant fisheries management strategy in the Global South, represents a special form of effort regulation. In these fisheries, a total number of licenses is specified, often in combination with other measures such as seasonal fishing bans (FAO, 2009; Shen and Heino, 2014; Tromeur and Doyen, 2018).

The fishing days system in the Faroe Islands is one of the most studied examples of effort regulation (Jákupsstovu et al., 2007; Baudron et al., 2010; Danielsen and Agnarsson, 2018). The system was introduced in 1996 to manage the demersal fisheries with cod, haddock and saithe as their main targets. While sometimes hailed as highly successful, a 10-years appraisal study by Jákupsstovu et al. (2007) showed that Faroese Total Allowable Effort (TAE) system did not achieve some of its key objectives, namely controlling the fishing mortality of the key species. This conclusion has been upheld by later assessments (Danielsen and Agnarsson, 2018). Most fishers opportunistically targeted the most valuable species, cod, leading to high levels of mortality for this valuable stock even when less abundant. The design of TAE system in the Faroe Islands relied on the assumption that when fishers choose their target species to maximize their profit, they target the species that provide the highest catch rates and ‘automatically’ protect the less abundant species with lower catch rates (Jákupsstovu et al., 2007; Baudron et al., 2010; Danielsen and Agnarsson, 2018). However, this is an assumption rather than a fundamental property of effort-controlled fisheries.

Previous studies on TAE regulation have often been conducted in a single species setting and in comparison with TACs; for example, fishing vessel behaviour under TAE and TAC regulation (Anderson, 1999; Stefansson and Rosenberg, 2005), and the effect of uncertainty on the efficiency of catch or effort controls (Danielsson, 2002; Yamazaki et al., 2009). Another strand of literature examined the degree of input substitution between restricted inputs and unrestricted inputs in a TAE system. Examples include the substitution intensity of restrictions on fishing days versus restrictions on vessel tonnage of the British Columbia commercial salmon fishery (Dupont, 1991), and the substitution between physical inputs and fishing location of the UK beam trawl fishery (Pascoe and Robinson, 1998). Until now, effort regulation has been assessed in a context of specific fishery systems. However, case-specific detail may hinder identifying the key factors that determine the success (or failure) of effort regulation in mixed fisheries.

The key factors affecting fishers’ targeting decision in mixed-fisheries have previously been studied piece by piece; for example, Katsukawa and Matsuda (2003) focused on the effect of non-linear catchability, Noailly et al. (2003) on the effect of price on switching harvest strategies, and Tromeur and Doyen (2018) on the effect of technical interactions. As a result, the conclusions of these papers may differ depending on specific underlying assumptions. When perfect separability is assumed, target switching may be able to protect the less abundant species from being overfished (Katsukawa and Matsuda, 2003; Bischi et al., 2013a,b); when joint production is unavoidable, species with lower price and growth but higher intraspecific competition and catchability are more prone to overfish, as concluded by Tromeur and Doyen (2018). We attempt to study all these key aspects together to give a more holistic picture about their interplay. We are specifically interested in effort regulation of mixed fisheries, but our results can be interpreted more generally as representing profit-oriented, effort-limited exploitation that could occur in unregulated fisheries or in a single-owner case.

The purpose of this paper is to present a generic analysis of factors determining the practicality of effort regulation using a simplified two-species fishery system. We generalize earlier models by treating separability and stock elasticity of harvest as parameters; the former describes fishers' ability to target and catch a specific species and the latter the degree of schooling behaviour of the fish. Our aim is to show when the effort regulation approach can work in terms of achieving the biological goal of not exhausting any of the species, or when it may not work, and why. The rest of the paper is organized as follows. The first section illustrates key factors governing fisherman's targeting decision and detailed model specifications. In the subsequent sections, we first present an analytical optimal harvest rule based on a common assumption about catchability parameter, followed by an evaluation of effort regulation based on a generic set-up using Monte Carlo simulations.

2 Methods

Identifying key factors

We start by identifying three key factors that describe the dynamics of a mixed fishery: the relative abundance and catchability of fish stocks, which determine the potential catch rates; the relative price for different fish species, which relates to the revenues obtained; and the ability of fishermen to catch the favoured species separately from the unfavoured species. These three factors form the cornerstones of effort regulation (Fig. 1).

Catchability is a species-specific parameter that describes the efficiency of fishing operation in catching a certain type of fish, therefore depending on both characteristics of the target (e.g., fish behaviour) and the fishing operation (e.g., efficiency of the fishing gears). Typically, catchability q of species i is defined through a linear relationship between catch rate (C_i), effort (E), and stock abundance (N_i), $C_i = q_i E N_i$. However, this simple model is

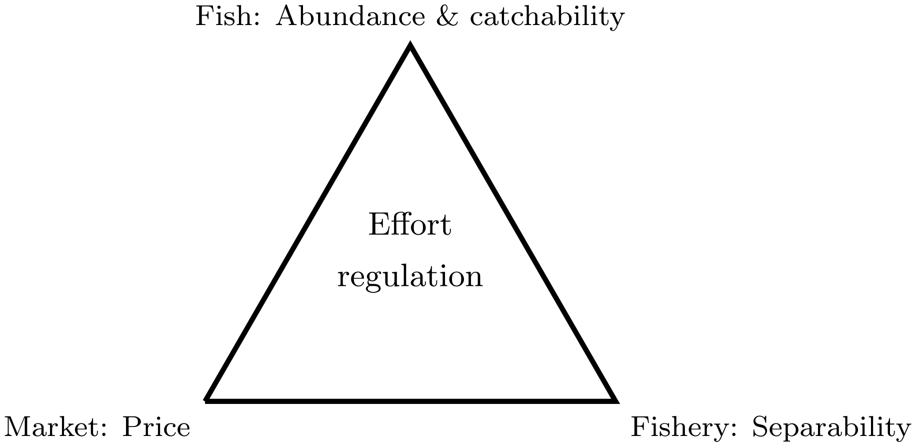

Figure 1: Key factors determining the practicality of effort regulation

often acknowledged to be inappropriate (Winters and Wheeler, 1985; Hilborn and Walters, 1992; Harley et al., 2001); for instance, a high catch per unit effort (C/E) for schooling species can still be maintained even at a low level of stock abundance. We thus follow the alternative formulation proposed by Steinshamn (2011) and Liu and Heino (2013) where catchability is measured in terms of the local stock density ρ experienced by a fisher:

$$C_i = q_i E \rho_i = \tilde{q}_i E N_i^{b_i} = a_i q_i N_i^{b_i-1} E N_i, \text{ with } \rho_i = a_i N_i^{b_i}. \tag{1}$$

Thus $\tilde{q}_i$ in Eq. 1, termed local catchability, is analogous with q_i in the classic formulation, but it has absorbed the scaling parameter a_i and is measured relative to local density ρ_i. N_i is stock abundance normalized against carrying capacity K_i. Parameter b_i is stock elasticity of harvest, with a typical value between $0 \leq b_i \leq 1$. The limit case ($b_i = 0$) refers the species that is extremely schooling and the fishers can locate the schools perfectly. $b_i = 1$ represents a non-schooling species that is uniformly distributed.

The influence of the market is captured by the relative price of the two species. We consider two ways of price determination: i) exogenous price, in which price is constant, and ii) endogenous price, in which price is a decreasing function of the catch. Specifically,

$$p_i(C_i) = \max\left(0, p_{i,0}\left(1 - \omega_i\left(C_i - C_{i,0}\right)\right)\right), \tag{2}$$

where $p_{i,0}$ is the initial unit price and $p_{i,0}\omega_i$ is the slope of the price function. When $\omega_i = 0$, $pi = p_{i,0}$ and the price is constant (exogenous price); when $\omega > 0$, price is endogenous, with higher total catches resulting in reduced unit price. The price $p_{i,0}$ is obtained when $C_i = C_{i,0}$, where $C_{i,0}$ is the optimal catch on the first fishing day when $\omega_i = 0$. That is to say, we express the price relative to the price obtained during the first fishing trip.

The final element in our model is 'separability' (τ). This is a fishery-level parameter and refers to fishers' ability to catch the favoured species, or in economics jargon, to the degree of joint production. It depends on biological factors (e.g., intrinsic differences in behaviour and micro-habitat use of the alternative species), fishers' skill of using these differences in fishing, and available fishing technologies that fishers can utilize (Branch and Hilborn, 2008; Squires et al., 2017). We take $\tau = 1$ to mean perfect separability where only the targeted species is caught, and $\tau = 0$ complete inability to catch species separately such that the total effort is equally shared among the two harvested species. For every unit of fishing effort made by a fisherman (e_i), only fraction $\frac{1+\tau}{2}$ is effectively converted into catching the target species (i), whereas fraction $\frac{1-\tau}{2}$ 'leaks' to the other species, leading to its bycatch. Thus, we differentiate the nominal effort targeted on species i, e_i, and the effective effort E_i, where $E_i = \frac{1+\tau}{2}e_i + \frac{1-\tau}{2}e_{-i}$ and e_{-i} denotes effort targeting the other species.

Biological model and assessment criteria

We model a simple fishery system consisting of two species that share the same overall habitat but are otherwise independent. Discarding is assumed not to occur. Our model focuses on stock dynamics in a single fishing season, which comprises a number of fishing trips of equal length; the length is inconsequential for our analysis and we will assume daily trips for convenience. Recruitment is assumed to occur outside the fishing season and can thus be ignored.

If stock abundance in the beginning of a fishing day/trip is N_0, it will drop to N_t in the end of that fishing trip due to natural and fishing mortality. The stock dynamics [1] is specified in the following:

$$N_t = \begin{cases} N_0 e^{-(F_t+M)} = N_0 e^{-(\tilde{q}E_t+M)t} & \text{if } b = 1, \\ \left\{ \left[N_0^{1-b} + \frac{\tilde{q}E_t}{M} \right] e^{-M(1-b)t} - \frac{\tilde{q}E_t}{M} \right\}^{\frac{1}{1-b}} & \text{if } 0 \leq b < 1. \end{cases} \tag{3}$$

where F and M are respectively fishing and natural mortality. Other notations follow Eq. 1.

The key question is whether profit-oriented fishing can lead to protection of the less abundant species? We use the stock size ratio as the metric to assess this question. As long as natural mortality during the fishing season is negligible, changes in this metric are driven by harvesting. If the stock ratio in the end of the fishing season $r_T = N_1^T / N_2^T$ is closer to unity than the initial stock ratio $r_0 = N_1^0 / N_2^0$, then the originally less abundant species must have suffered less from fishing than the other species. In other words, it has been offered a degree of protection. This is a necessary condition for effort regulation to have the potential to be successful. We emphasize, however, that this criterion is not a sufficient condition to ensure sustainable fisheries, because it does not address simultaneous stock depletion. This could be prevented by setting the total effort quota sufficiently low; the determination of suitable total effort is beyond the scope of our current analysis.

We consider two basic scenarios in our analysis: (a) ‘even’ scenario in which two species in the mixed fishery have the same initial stock (i.e., $r_0 = N_1^0 / N_2^0 = 1$); (b) ‘biased’ scenario in which their initial stock levels are different (here $r_0 = 2$). In the former case, the success criterion is that the final stock size ratio r_T does not deviate too much from unity, and in the latter case, that the final stock size ratio r_T has moved closer to unity.

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[1] The expression for N_t is derived via integrating over a full fishing trip $\frac{dN}{dt} = -(F+M)N$, and $F = \tilde{q}N^{b-1}E$. For detailed derivation see Steinshamn (2011); Liu and Heino (2013)

Profit maximizing fleet

The goal of the fleet manager is to maximize her payoffs per fishing trip for the entire fleet. We define effort in terms of fishing days. The total allowable fishing days per fishing season allocated to a fleet is set at Q. We assume the fleet consists of n identical boats. The strategy option for the manager is to decide the number of boats to target different species $i \in (1,2)$. The maximization will be repeated for each fishing trip until Q is exhausted or profit turns negative. We formulate trip-level profit maximization as follows:

$$\begin{aligned} V_t &= \max_{e_{i,t}} \sum_n \sum_i \left(\int_0^{C(E_{i,t})} p_i(C)dC - ce_{i,t} \right), i \in (1,2) \\ s.t. & \begin{array}{ll} \sum_i e_{i,t} & \leq n \textit{ (Fleet capacity)} \\ \sum_t \sum_i e_{i,t} & \leq Q \textit{ (Effort control)} \\ E_{i,t} & = \frac{1+\tau}{2} e_{i,t} + \frac{1-\tau}{2} e_{-i,t} \textit{ (Separability)} \\ V_t & \geq 0 \textit{ (Non-negativity)} \end{array} \end{aligned} \tag{4}$$

where price of fish p_i is determined by the price function in the Eq. 2; c is cost per unit effort, e and E denote respectively nominal effort and effective effort. Provided that the species are not fully separable, Eq. 4 gives two sources of income streams from each species. C denotes total catch per trip, given by the function by Liu and Heino (2013), based on the catchability definition in Eq. 1:

$$\begin{aligned} C_t &= \tilde{q}E_t \int_0^1 N_t^b dt \\ &= \begin{cases} \frac{F_t}{F_t+M} N_0 (1 - e^{-(F_t+M)}) = \frac{\tilde{q}E_t}{\tilde{q}E_t+M} N_0 (1 - e^{-(\tilde{q}E_t+M)t}) & \text{if } b = 1, \\ \tilde{q}E_t \int_0^1 \left\{ \left[N_0^{1-b} + \frac{\tilde{q}E_t}{M} \right] e^{-M(1-b)t} - \frac{\tilde{q}E_t}{M} \right\}^{\frac{b}{1-b}} dt & \text{if } 0 \leq b < 1. \end{cases} \end{aligned} \tag{5}$$

The maximization problem in Eq. 4 is subject to several constraints: (1) fleet capacity constraint: total fishing boats per trip shall not exceed the fleet capacity n, assuming trip length of 1 day/trip; (2) effort constraint: total fishing days per season is no more than Q; (3) species separability constraint: only part of the effort is converted into effective effort;

and (4) non-negative profit per fishing trip.

Because more boats targeting the same species result in faster depletion of the resource, and may influence the price (if $\omega > 0$), the optimal decision of one fisherman depends on what other fishermen decide to do. This can potentially lead to a game-like situation, but this is avoided if we assume that the decision horizon is one fishing trip (e.g., 1 day) only, and the problem reduces to a simple optimization task analogous to 'perfect competition' of identical competitors in economics, or 'ideal free distribution' in ecology (Fretwell and Lucas, 1969). Thus, to understand the collective behaviour of individual fishermen, we can simply find the distribution of effort that maximizes the collective pay-off per fishing trip. The solutions of the model correspond to optimal policies in a single owner case too.

Monte Carlo sampling method

The model is not analytically tractable except for some special cases. To obtain an overview on how key factors affect the performance of effort regulation, we turn to the Monte Carlo method of repeated random sampling approach. Key factors and their assumptions are summarized in Table 1 and are very general. We assume b and τ to follow uniform distribution because they are naturally bounded between 0 and 1 (while b could exceed 1, $b = 1$ is a defensible upper limit, see Steinshamn (2011)). Price and catchability ratios are assumed to be log-normally distributed such that the mean ratio is one. The results are based on 50,000 random replicates.

3 Optimal harvest decisions in a mixed fishery

A static setting

For the case of uniformly distributed fish stock ($b = 1$), we can analytically show that optimal harvest decision in our model is characterized by the relative marginal profit of effort (MPE) of the two stocks, i.e., the difference in the marginal increase of profit when

Table 1: Key assumptions for Monte Carlo sampling. Actual levels of prices and costs are immaterial as long as fishing is profitable.

Parameter	Description	Value	Distribution
τ	separability	$0 \leq \tau \leq 1$	uniform
b	stock elasticity of harvest	$0 \leq b \leq 1$	uniform
$\log(\frac{p_1}{p_2})$	price ratio	$\mu = 0, sd = 0.5$	normal
$\log(\frac{\tilde{q}_1}{\tilde{q}_2})$	catchability ratio	$\mu = 0, sd = 0.5$	normal
ω_i	slope of the price function	0 or 50	n.a.
M_i	natural mortality	0.2 yr^{-1}	n.a.
Q	effort quota	1000 days	n.a.
n	fleet capacity	20	n.a.

Note: μ denotes mean and sd standard deviation.

effort targeting a specific species is increased. We can distinguish three cases:

- If $\text{MPE}_1 > \text{MPE}_2$, then only species 1 is harvested ($e_1 > 0$ and $e_2 = 0$).
- If $\text{MPE}_1 < \text{MPE}_2$, then only species 2 is harvested ($e_1 = 0$ and $e_2 > 0$).
- If $\text{MPE}_1 = \text{MPE}_2$, then both species are harvested ($e_1 > 0$ and $e_2 > 0$).

The expression for MPE in the general case is too complicated to yield insight (see the Appendix). However, if we assume that natural mortality is insignificant over short time periods and can be ignored ($M = 0$), $\text{MPE}_1 > \text{MPE}_2$ if $p_1\tilde{q}_1N_1e^{-\tilde{q}_1E_1} > p_2\tilde{q}_2N_2e^{-\tilde{q}_2E_2}$. High price p and initial stock N will therefore favour targeting one stock over the other. The role of catchability $\tilde{q}$ is ambiguous because its effect can be either positive or negative, depending on the other parameters.

When fishers cannot discriminate the two species ($\tau = 0$), every unit of effort is equally divided between them, and any effort allocation satisfying the fleet capacity constraint will be optimal. This is a trivial case, and in the subsequent discussion we will focus on the case $\tau > 0$ only.

Seasonal patterns of harvest decisions

Because a fishing season consists of a number of fishing trips in our model, we will study how MPE evolves over time. There are three generic patterns of time evolution in the model:

- A single species is the sole target species during the whole fishing season. MPE of one species is always greater than the other.
- A single species is the sole target species in the beginning of the fishing season. After MPEs are equalized between the species, both species are targeted.
- A single species is the sole target species in the beginning of the fishing season. MPEs switch the rank that leads to a target switch, i.e., the other species becomes the sole target.

The first two cases follow naturally from the rules of optimal harvest described in the previous section: the fishermen will target the more profitable stock, or if both stocks are equally profitable, they will split their effort such that the equal profitability is maintained. Initially, one stock is almost always more profitable. Whether targeting the more profitable species leads to equal profitability during the period of interest depends on the details. First, while targeting one species will often cause the MPEs to converge towards each other, this is not always the case. MPEs may diverge if separability τ is low, or if one species has higher natural mortality M than the other. Second, even when targeting one species is causing the MPEs to converge, full equalization might not be reached during the available fishing season.

Fig. 2a–c illustrates how targeting one species reduces its profitability, eventually resulting in the situation in which both species have similar MPEs. In this example, species 1 has initially a higher MPE and is the sole target during the first part of the season. Over time, MPE for the target species 1 decreases more than MPE for the bycatch species 2 because fishing reduces its abundance more than that of the bycatch species. When both species reach the same MPE level, the effort (Fig. 2b) is divided between the two species such that the MPE equality is maintained. In this example, effort regulation first causes divergence in the relative stock abundances, followed by rebalancing and divergence to the other direction.

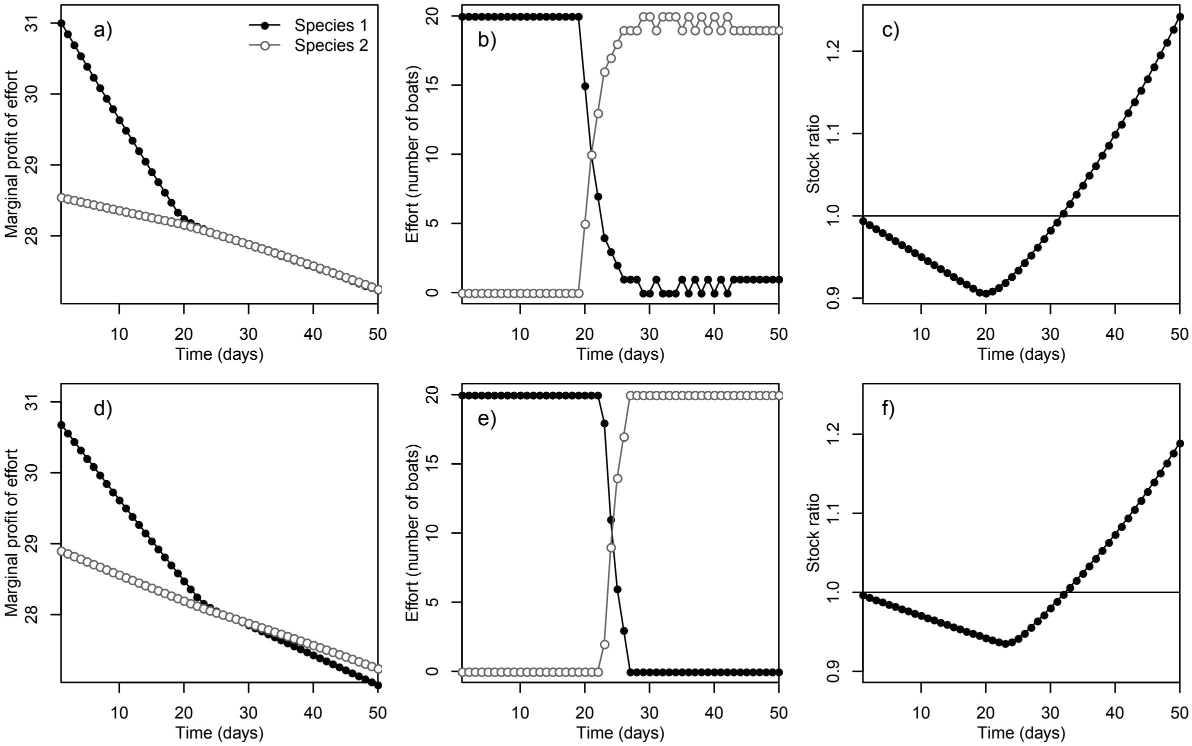

Figure 2: Two qualitatively different scenarios of marginal profit of effort and effort allocation over time, together with the corresponding relative stock size. On the top row (a–c), separability is high ($\tau = 0.8$). Two distinct phases are observed: first, only the species 1 that is more profitable is targeted, and second, once the profitability of species 1 is reduced to that of species 2, both species are targeted with an effort allocation that keeps their profitability similar. On the bottom row (d–f), separability is lower ($\tau = 0.57$). This leads to dynamics that are initially similar, but instead of profitability equalization, the initial bycatch species becomes the sole target. Parameters other than τ are equal for both scenarios: $N_0 = [0.5, 0.5]$, $b = [0.813, 0.086]$, $p = [53924, 100000]$, $\tilde{q} = [0.0003, 0.0003]$, $\omega = [0, 0]$, $c = 0.1$, $Q = 1000$.

The dynamic in the third case where the MPE curves of two species cross each other and the fishermen switch their target species is more intricate. Fig. 2d–f illustrates how such target switching can result from effort ‘spill-over’. Fishermen first target the more profitable species 1. As its profitability declines, both species 1 and 2 become targeted. At this point, it is possible that even when species 2 is the sole target, species 1 is caught so much as bycatch that its MPE stays lower than that of the target species. We will elaborate further on this point in the Section 4 when discussing reinforcing effect.

4 Assessing performance of effort regulation through Monte Carlo simulations

The overall performance of effort regulation

We assess performance of effort regulation by simulating a large number (50,000) of cases generated by sampling a realistic parameter space (Table 1). When the fisheries are initiated with two species at equal abundance, effort regulation can often keep the relative stock levels within 'reasonable' bounds. Specifically, if we require that the stock ratio N_1^T/N_2^T at the end of fishing season remains within the interval $[0.5, 2]$ (i.e., the less abundant species has density at least 50% of that of the more abundant species), effort regulation is successful in 87% of the cases (Fig. 3a). However, if the fisheries are initiated with one species being twice as abundant as the other one, the chances of effort regulation meeting the same success criterion are considerably lower, about 51% (Fig. 3b). In these cases, effort regulation has either maintained the original biased stock ratio, or 'corrected' it towards equality. However, there is also a sizeable proportion of cases – 40% – where the relative stock abundance becomes driven towards more extreme bias in favour of the originally more abundant species. In the remaining fraction of the cases, the originally less abundant species becomes more abundant as a result of fishing.

Single-factor effects

We now investigate the characteristics of the cases where effort regulation can be successful. Figures 4 and 5 show the density distributions of the final stock ratio against key parameters that we varied. They reveal two main patterns. First, the fishers' ability to catch target species, separability τ (the only stock-unspecific parameter we varied), has

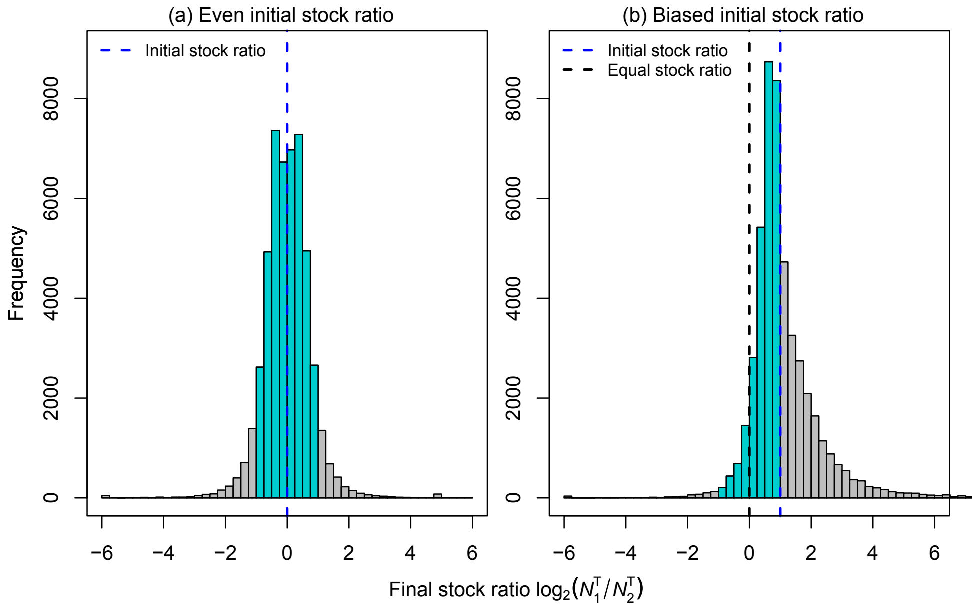

Figure 3: Histogram of stock ratio in the end of the fishing season for (a) even ($N_1^0 = N_2^0$) and (b) biased initial stock ratio ($N_1^0/N_2^0 = 2$). Cyan bands indicate the range where end stock ratio is seen as 'reasonable', defined as $N_1^T/N_2^T \in [0.5, 2]$. Price is constant ($\omega = [0, 0]$); other parameters as detailed in Table 1.

an important role. When separability is low ($\tau \to 0$), stock ratio at the end of the season usually stays near its initial value, be it equal or biased (Fig. 4a and 5a). However, when separability is high ($\tau \to 1$), the stock ratio diverges away from its initial value, in one direction or the other. If the initial stock abundances are even, then a bimodal distribution emerges (Fig. 4a). If the initial relative stock abundances are biased, then the final stock ratio shows a unimodal but skewed distribution (Fig. 5a). Across all τ, there is a tendency for the stock ratio to move closer to unity; the average final stock ratio is $N_1^T/N_2^T 0 \approx 1.15$, although there is a long tail of cases towards more extreme bias (Fig. 5a). Nevertheless, in an average sense, effort regulation offers a degree of protection for the less abundant stock when starting from unequal initial abundances.

Second, the parameters that are stock-specific show similar patterns. If the relative stock abundances are initially even, the abundances at the end of season have best chances of maintaining the status quo when the species are similar in terms of their schooling parameter b, catchability $\tilde{q}$, and price p (Fig. 4b–d). On the other hand, if the initial relative stock abundances are biased, then the similarity of the species, on average, tends to hinder equalization of relative abundances. However, if the species differences are such that the initially less abundant species is a more favourable target (higher price p or catchability $\tilde{q}$, or lower stock elasticity to harvest b), then equalization is more likely to happen (Fig. 5b–d). Differences in the opposite directions will consequently make equalization less likely.

Most Monte Carlo replicates in Figures 4 and 5 show targeting of the same species through the fishing season. This happens because MPEs of the two stock converge so slowly that they do not meet during the available time, or because of the bycatch effect that may even make them diverge. Equalization of MPEs followed by targeting of both species for the rest of the season (similar to Fig. 2a–c) happens only in about 15% of replicates. Target swapping (Fig. 2d–f) is even rarer, occurring in about 4% of replicates for the even initial scenario and less than 1% of replicates for the biased initial scenario.

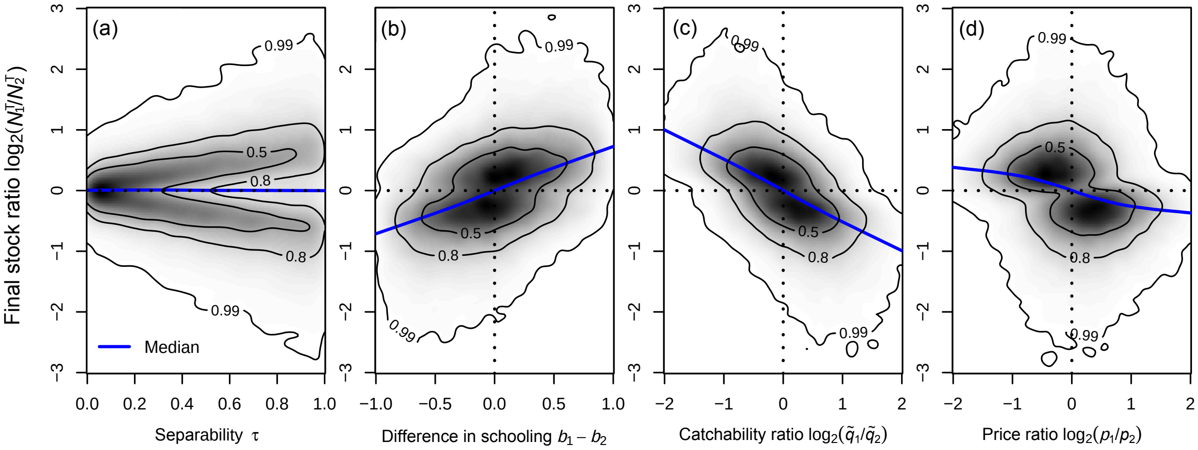

Figure 4: Density plots for the 'even' scenario (initial stock ratio $N_1^0/N_2^0 = 1$): black curves are contour lines, blue curves indicate the smoothed median density, and black dotted lines are reference level when the two species are symmetric. Price is declining with increasing catches ($\omega = [50, 50]$); other parameters as detailed in Table 1.

Interaction effects

When the species differ in more than one parameter, these differences could either reinforce or compensate for each other. For example, if one species has a higher unit price but

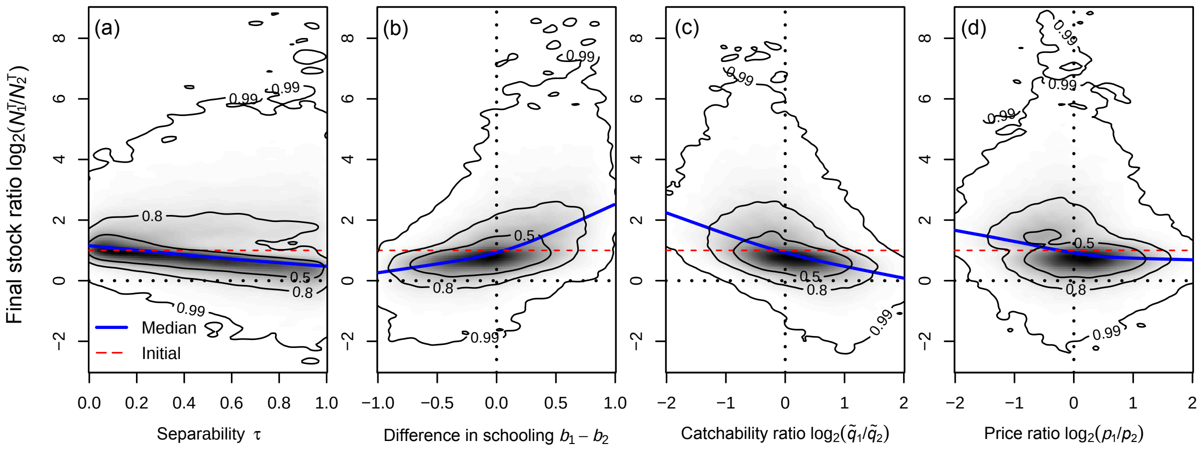

Figure 5: Density plots for the 'biased' scenario (initial stock ratio $N_1^0/N_2^0 = 2$ indicated by red dotted lines): black curves are contour lines, blue curves indicate the smoothed median density, and black dotted lines are reference level when the two species are symmetric. Price is constant ($\omega = [0,0]$); other parameters as detailed in Table 1.

lower catchability, it can be an equally attractive target to a cheaper species with higher catchability. This 'compensation effect' is seen in Figure 6 as contour lines that are tilted relative to the axes. In particular, a balanced final stock ratio can be achieved not only when the two species are similar, but also when they differ such that an attractive attribute is compensated by a less attractive one.

Conversely, when the species differ in multiple ways that work in the same direction, we observe a 'reinforcing effect'. This corresponds to the movement perpendicularly to the contour lines in Figure 6. In this case, even relatively small differences in the species-specific parameters may lead to large differences in the final stock ratio.

5 Discussion

We have addressed two questions that are pertinent to any effort control system: whether species that are originally balanced (i.e., similar in stock size) can be maintained at a relatively balanced level as a result of profit-oriented fishing, and secondly, whether profit-oriented fishing could conserve species that are at low levels, such that relative stock levels

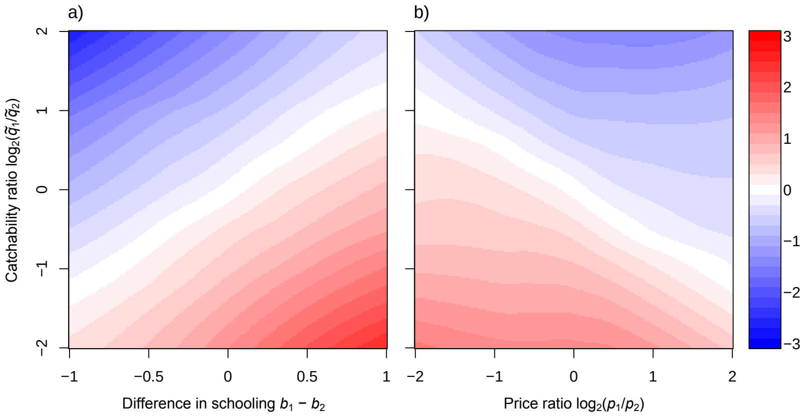

Figure 6: Parameter interactions under the even initial stock scenario for ratio of catchabilities ($\tilde{q}$) versus difference in the stock elasticity of (a) harvest (schooling, b) and (b) ratio of prices (p). Colour gradient shows the end stock ratio $\log_2(N_1^T/N_2^T)$. High stock differences are found when the effects of two factors are reinforcing each other. Similar stock levels appear around the mid-range area shown in white.Price is constant ($\omega = [0,0]$); other parameters as detailed in Table 1.

would be more balanced after the fishing season—a necessary, but not sufficient, condition for a sustainable use of an ecosystem. We have addressed these questions using a generic two-species dynamic bio-economic model, assuming fishers that are omniscient and profit-maximizing. Our main finding is that effort regulation is prone to exaggerating the stock abundance differences, particularly when the fishers are effective in selectively catching the more profitable species. Generally speaking, it is hard to achieve balanced relative stock levels. However, effort regulation may achieve its biological conservation goal under two general conditions:

1. The species are sufficiently similar with respect to the key factors that determine the profitability of their harvest.
2. When the key parameters counteract each other such that the resulting overall profitability is similar.

Concerning the latter case, a low catchability can be compensated by a higher price, and vice versa. On the contrary, if the key parameters reinforce each other, instead of counteracting, effort regulation can lead to increased differences in the relative stock levels, e.g.

fishers keep harvesting the less abundant species. The degree to which one stock gets depleted depends on the fleet's capacity to deplete the stock (the total allowable effort Q and catchability $\tilde{q}$) as well as on the degree to which high local density is maintained when stock is being depleted (stock elasticity of harvest b).

Empirical studies have established that fishers' behavioural choices can, to a large part, be understood based on their expectations on profits. Much of the evidence comes from studies on location choice (e.g., Eales and Wilen, 1986; Gillis et al., 1993; Andersen et al., 2010). Our model predicts that in the beginning of a fishing season, profit-maximizing fishers often target only a single stock. As that stock is fished down, its profitability declines and eventually equals that of the other stock. At this point, fishers would be expected to split their effort targeting both stocks. This kind of dynamic has been reported from the Turks and Caicos Islands, where the artisanal fishermen diversified their effort allocation after density of the initially favoured, more valuable target had sufficiently declined; price difference between the two targets was constant and did not influence targeting (Béné and Tewfik, 2001).

Because profitability reflects a range of biological and economic parameters, target switches can occur in response to various factors, singly or together. For example, in demersal fisheries of Northeast Atlantic, changes in catchability caused by technological change are an important factor explaining long-term changes in target species (Marchal et al., 2006). In a mixed coastal trawl fishery in Taiwan, the fishers responded to day-to-day price fluctuations by increasing catches of species with positive price signals (Liu et al., 2018). The failure of the Faroese fisheries to switch away from catching depleted species was likely caused by price compensation (Jákupsstovu et al., 2007). Studies of small-scale fishermen have shown simultaneous influences of seasonal fluctuations in catchability and changes in price that lead to target switching (Salas et al., 2004; Naranjo-Madrigal and Bystrom, 2019).

Our results show that differences in stock elasticity of harvest (b), reflecting a stock's spacing behaviour and the fishers' ability to find the fish, can be as important as differences in the parameters traditionally emphasized when estimating revenues, namely catchability and price (Fig. 4 and 5). While it is commonly acknowledged that the relationship between fish abundance and catch may not be linear, theoretical analyses typically assume that stock elasticity of harvest is unit-elastic ($b = 1$) or perfectly inelastic ($b = 0$; see Steinshamn, 2011; Liu and Heino, 2013). Differences in b imply that the relative profitability of two species might switch ranks even when they both see similar proportional reduction in abundance. We are not, however, aware of any examples where changing in targeting can be explained by differences in b. While empirical analyses will implicitly account for this effect, it is probably difficult to detect in practice. Nevertheless, our results show that effort regulation is likely to fail when a mixed fishery is composed of a schooling and a non-schooling species.

Separability, or the ability of fishers to target and catch a species separately from others, has a multifaceted role in effort regulation of mixed fisheries. The fishers' ability to target the more abundant species lies at the core of the idea that effort regulation can protect species that are at low abundance. Our results show that separability is indeed necessary for fishery to be able to selectively harvest the more abundant species (Fig. 5a). However, strong separability also increases the risk of seriously depleting one of the species (Figs. 4a and 5a), which can happen when one species has much higher price, catchability, and/or schooling tendency than the other. When separability is poor, such extreme outcomes are mostly avoided, but poor separability also prevents fishers from fishing down the more abundant species (Fig. 5a). The effect of separability is approximately linear, such that studies assuming perfect separability (Katsukawa and Matsuda, 2003; Bischi et al., 2013a,b) and complete lack of separability (Tromeur and Doyen, 2018) capture the extremes—realistic situations likely lie somewhere in between.

It is worth noting that effort regulation incentivizes fishers to improve separability only when it helps them to increase the total value of their catches; there is no disincentive per se for catching non-target species. This is in stark contrast to catch quota regulation where lack of separability may prevent fisheries from fully utilizing quotas of some species (e.g., Kuriyama et al., 2016; Mortensen et al., 2018), hence incentivizing investments to technology that improves separability. In any case, the degree to which fishers can adapt their catch profiles is a core question for mixed-fisheries management (Hoff et al., 2010).

Our model includes only two species, while most fisheries are considerably more diverse. Our analysis indicates that profit-oriented exploitation can help to maintain a balance between two exploited species, but also that this requires a fortuitous balance between a number of biological and economic parameters. It is worth emphasizing that the higher is the number of exploitable species in a system, the more likely is that at least one of them does not meet this fortuitous balance. Therefore, challenges in using effort to regulation to manage mixed fisheries will increase with increasing species diversity.

In our analysis, we have solely focused on stock dynamics during a single fishing season. Dynamics between fishing seasons could either exacerbate or alleviate the differences in stock levels, depending on the processes related to biomass gain and loss (i.e., gain from recruitment of new individuals and body growth of existing individuals, and loss through mortality) that are stock-specific. Because of density-dependent effects, we can offer some general insights. If a stock is below the stock level that corresponds to maximum biomass production—and maximum sustainable yield (MSY)—then its biomass production will usually increase with increasing stock size. This implies that the relatively more depleted stock will also, on average, have lower biomass production, exacerbating the already existing difference in the stock levels. On the other hand, if two stocks are larger than their respective MSY levels, then the larger stock will see less growth, and the difference in the stock levels is expected to decline. This suggests that effort regulation is more likely to afford a degree of protection to less abundant stocks when most stocks are at healthy levels (near MSY or higher), but that trusting effort regulation to conserve already depleted stocks will be particularly pernicious.

Based on our numerical results and the arguments presented above, we suggest that effort regulation is most likely to succeed when (1) the fishery is catching only a few species, (2) these species are biologically similar and have similar market niches (such that the parameters determining revenues are similar), and (3) the species are at ‘healthy’ abundance levels. The first two conditions are probably most likely to be fulfilled in cold-water ecosystems where species diversity is low and taxonomically closely related species such as gadids dominate catches. Conversely, effort regulation is likely to fail to protect at least some species in species-rich temperate and tropical ecosystems—even more so when the fisheries already are overexploited, such as in the Mediterranean Sea, where effort regulation is a part of the management toolbox and the overall status of fisheries resources remains poor (FAO, 2018). However, the fact that the effort control system for the Faroese demersal fisheries came close to fulfilling the first two desiderata and yet failed suggests that effort control lacks robustness even under relatively favourable conditions.

The fragility of effort regulation is further increased if markets are paying a price premium for rare species, as is the case for, e.g., Pacific bluefin tuna in Japan (Tokunaga, 2017). This effect could be countered by consumer awareness campaigns, which have been successful in the past in promoting more sustainable fishing practices (Jacquet et al., 2010).

Effort regulation is sometimes advocated as the solution to problems in managing mixed fisheries that is simpler, more flexible, and easier to implement than species-specific TAC regulation (Pope, 2002; European Commission, 2012). While some of these advantages are undeniable, our results warn against placing too much confidence on the ability of effort regulation to provide automatic protection for species that are depleted. Protection is only expected to occur when the targeted species initially offer similar profitability. This requires a fortuitous balance between a range of biological and economic parameters, which can be easily broken by exogenous or endogenous changes in prices. In this regards, supplementary regulations such as area management and gear restriction are needed, and a combination of TAC and TAE is sometimes more favourable (Squires et al., 2017).

Acknowledgements

We thank Daigee Shaw, Chih-Ming Hung and Yu-Lan Chien for comments on earlier drafts of this paper. The feedback by three anonymous reviewers and the editor Raúl Prellezo helped to considerably improve this paper. We acknowledge the Norwegian Research Council (grants 255530 and 288037) and the EU H2020 ERC Starting Grant project CLOCK (grant 679812) for support.

References

Alzorriz, N., Jardim, E., and Poos, J. J. (2018). Likely status and changes in the main economic and fishery indicators under the landing obligation: A case study of the Basque trawl fishery. *Fisheries Research*, 205:86–95.

Andersen, B. S., Vermard, Y., Ulrich, C., Hutton, T., and Poos, J.-J. (2010). Challenges in integrating short-term behaviour in a mixed-fishery Management Strategies Evaluation frame: A case study of the North Sea flatfish fishery. *Fisheries Research*, 102(1–2):26–40.

Anderson, L. G. (1999). The microeconomics of vessel behavior: a detailed short-run analysis of the effects of regulation. *Marine Resource Economics*, 14(2):129–150.

Baudron, A., Ulrich, C., Nielsen, J. R., and Boje, J. (2010). Comparative evaluation of a mixed-fisheries effort-management system based on the Faroe Islands example. *ICES Journal of Marine Science*, 67(5):1036–1050.

Béné, C. and Tewfik, A. (2001). Fishing effort allocation and fishermen's decision making process in a multi-species small-scale fishery: analysis of the conch and lobster fishery in Turks and Caicos Islands. *Human Ecology*, 29(2):157–186.

Bischi, G.-I., Lamantia, F., and Radi, D. (2013a). Multispecies exploitation with evolutionary switching of harvesting strategies. *Natural Resource Modeling*, 26(4):546–571.

Bischi, G.-I., Lamantia, F., and Radi, D. (2013b). A prey–predator fishery model with endogenous switching of harvesting strategy. *Applied Mathematics and Computation*, 219(20):10123–10142.

Branch, T. A. and Hilborn, R. (2008). Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behavior under individual transferable quotas. *Canadian Journal of Fisheries and Aquatic Sciences*, 65(7):1435–1446.

Daan, N. (1997). TAC management in North Sea flatfish fisheries. *Journal of Sea Research*, 37(3–4):321–341.

Danielsen, R. and Agnarsson, S. (2018). Fisheries policy in the Faroe Islands: Managing for failure? *Marine Policy*, 94:204–214.

Danielsson, A. (2002). Efficiency of catch and effort quotas in the presence of risk. *Journal of Environmental Economics and Management*, 43(1):20–33.

Dupont, D. P. (1991). Testing for input substitution in a regulated fishery. *American Journal of Agricultural Economics*, 73(1):155–164.

Eales, J. and Wilen, J. E. (1986). An examination of fishing location choice in the pink shrimp fishery. *Marine Resource Economics*, 2(4):331–351.

European Commission (2012). Fishing effort–fact sheet. `https://ec.europa.eu/fisheries/cfp/fishing_rules/fishing_effort_en`. Online; access 10 March 2018.

European Union Committee (2008). The progress of the Common Fisheries Policy. `http://webarchive.parliament.uk/20120302190331/http://www.publications.parliament.uk/pa/ld200708/ldselect/ldeucom/146/146.pdf`. Online; access 15 March 2018.

FAO (2009). *The State of World Fisheries and Aquaculture 2008*. FAO, Rome.

FAO (2018). *The State of Mediterranean and Black Sea Fisheries*. General Fisheries Commission for the Mediterranean, Rome.

Fretwell, S. D. and Lucas, H. L. (1969). On territorial behavior and other factors influencing habitat distribution in birds. *Acta Biotheoretica*, 19(1):16–36.

Gillis, D. M., Peterman, R. M., and Tyler, A. V. (1993). Movement dynamics in a fishery: application of the ideal free distribution to spatial allocation of effort. *Canadian Journal of Fisheries and Aquatic Sciences*, 50(2):323–333.

Harley, S. J., Myers, R. A., and Dunn, A. (2001). Is catch-per-unit-effort proportional to abundance? *Canadian Journal of Fisheries and Aquatic Sciences*, 58(9):1760–1772.

Hilborn, R., Stokes, K., Maguire, J.-J., Smith, T., Botsford, L. W., Mangel, M., et al. (2004). When can marine reserves improve fisheries management? *Ocean & Coastal Management*, 47:197–205.

Hilborn, R. and Walters, C. J. (1992). *Quantitative fisheries stock assessment: choice, dynamics and uncertainty*. Chapman and Hall.

Hoff, A., Frost, H., Ulrich, C., Damalas, D., Maravelias, C. D., Goti, L., and Santurtún, M. (2010). Economic effort management in multispecies fisheries: the FcubEcon model. *ICES Journal of Marine Science*, 67(8):1802–1810.

Jacquet, J., Hocevar, J., Lai, S., Majluf, P., Pelletier, N., Pitcher, T., et al. (2010). Conserving wild fish in a sea of market-based efforts. *Oryx*, 44(1):45–56.

Jákupsstovu, S., Cruz, L., Maguire, J., and Reinert, J. (2007). Effort regulation of the demersal fisheries at the Faroe Islands: a 10-year appraisal. *ICES Journal of Marine Science*, 64(4):730–737.

Katsukawa, T. and Matsuda, H. (2003). Simulated effects of target switching on yield and sustainability of fish stocks. *Fisheries Research*, 60(2-3):515–525.

Kuriyama, P. T., Branch, T. A., Bellman, M. A., and Rutherford, K. (2016). Catch shares have not led to catch-quota balancing in two North American multispecies trawl fisheries. *Marine Policy*, 71:60–70.

Laurec, A., Biseau, A., and Charuau, A. (1991). Modelling technical interactions. *ICES Marine Science Symposia*, 193:225–236.

Liu, X. and Heino, M. (2013). Overlooked biological and economic implications of within-season fishery dynamics. *Canadian Journal of Fisheries and Aquatic Sciences*, 71(2):181–188.

Liu, X., Shaw, D., Bjørndal, T., and Heino, M. (2018). The supply response of small-scale fishers in license-controlled mixed fisheries. In *6th World Congress of Environmental and Resource Economists*. 25–29 June 2018, Gothenburg, Sweden.

Marchal, P., Andersen, B., Caillart, B., Eigaard, O., Guyader, O., Hovgaard, H., et al. (2006). Impact of technological creep on fishing effort and fishing mortality, for a selection of European fleets. *ICES Journal of Marine Science*, 64(1):192–209.

Mortensen, L. O., Ulrich, C., Hansen, J., and Hald, R. (2018). Identifying choke species challenges for an individual demersal trawler in the North Sea, lessons from conversations and data analysis. *Marine Policy*, 87:1–11.

Mulazzani, L., Camanzi, L., Bonezzi, A., and Malorgio, G. (2018). Individual transferable effort quotas for Italian fisheries? A preliminary analysis. *Marine Policy*, 91:14–21.

Naranjo-Madrigal, H. and Bystrom, A. B. (2019). Analyzing fishing effort dynamics in a multispecies artisanal fishery in Costa Rica: social and ecological system linkages. In Salas, S., Barragán-Paladines, M. J., and Chuenpagdee, R., editors, *Viability and Sustainability of Small-Scale Fisheries in Latin America and The Caribbean*, MARE Publication Series, pages 379–404. Springer International Publishing, Cham.

Noailly, J., van den Bergh, J. C., and Withagen, C. A. (2003). Evolution of harvesting strategies: replicator and resource dynamics. *Journal of Evolutionary Economics*, 13(2):183–200.

Pascoe, S. and Robinson, C. (1998). Input controls, input substitution and profit maximisation in the English Channel beam trawl fishery. *Journal of Agricultural Economics*, 49(1):16–33.

Pope, J. (2002). Input and output controls: the practice of fishing effort and catch management in responsible fisheries. In Cochrane, K. L., editor, *A fishery manager's guidebook. Management measures and their application*, number 424 in FAO Fisheries Technical Paper, pages 75–93. FAO, Rome.

Salas, S., Sumaila, U. R., and Pitcher, T. (2004). Short-term decisions of small-scale fishers selecting alternative target species: a choice model. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(3):374–383.

Shen, G. and Heino, M. (2014). An overview of marine fisheries management in China. *Marine Policy*, 44:265–272.

Squires, D., Maunder, M., Allen, R., Andersen, P., Astorkiza, K., Butterworth, D., et al. (2017). Effort rights-based management. *Fish and Fisheries*, 18(3):440–465.

Stefansson, G. and Rosenberg, A. A. (2005). Combining control measures for more effective management of fisheries under uncertainty: quotas, effort limitation and protected areas. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360(1453):133–146.

Steinshamn, S. I. (2011). A conceptional analysis of dynamics and production in bioeconomic models. *American Journal of Agricultural Economics*, 93(3):803–812.

Tokunaga, K. (2017). Estimating elasticity of demand for Pacific bluefin tuna in Tsukiji fish market. *Marine Resource Economics*, 33(1):27–60.

Tromeur, E. and Doyen, L. (2018). Optimal harvesting policies threaten biodiversity in mixed fisheries. *Environmental Modeling & Assessment*, pages 1–17.

Vielmini, I., Perry, A. L., and Cornax, M. J. (2017). Untying the Mediterranean Gordian knot: a twenty first century challenge for fisheries management. *Frontiers in Marine Science*, 4:195.

Winters, G. and Wheeler, J. (1985). Interaction between stock area, stock abundance, and catchability coefficient. *Canadian Journal of Fisheries and Aquatic Sciences*, 42(5):989–998.

Yamazaki, S., Kompas, T., and Grafton, R. Q. (2009). Output versus input controls under uncertainty: the case of a fishery. *Natural Resource Modeling*, 22(2):212–236.

Appendix: Derivation of the optimal harvest rules

We rely on the Lagrangian conditions to characterize the optimal harvest rules. The scope of analysis in this section is limited to the case where the Baranov catch equation (also known as Beverton–Holt model) applies (i.e., $b = 1$ in Eq. 5) and when the price is exogenous.

We formulate the Kuhn-Tucker (KT) Lagrangian function of Eq. 4, and derive following KT conditions:

$$\frac{\partial \bar{L}}{\partial e_i} = \overbrace{A_i \frac{1+\tau}{2} + A_{-i} \frac{1-\tau}{2} - c}^{\text{Marginal profit of effort}} - \lambda \leq 0 \tag{6a}$$

$$e_i \frac{\partial \bar{L}}{\partial e_i} = 0 \text{ and } \lambda \Big(\sum_i e_i - n\Big) = 0 \tag{6b}$$

$$\lambda \geq 0,\ e_i \geq 0 \text{ and } \sum_i e_i \leq \min\Big(n, Q - \sum_{t=1}^{t-1} e_{i,t}\Big) \tag{6c}$$

where $A_i = p_i q_i N_i \left(\frac{M}{(E_i q_i + M)^2} (1 - e^{-(q_i E_i + M)}) + \frac{E_i q_i}{E_i q_i + M} e^{-(q_i E_i + M)} \right)$.

Note that $A_i \frac{1+\tau}{2} + A_{-i} \frac{1-\tau}{2} - c$ in Eq. 6a can be interpreted as marginal profit of effort (MPE). Analysis of Kuhn-Tucker conditions reveals a general optimal harvest rule ($\tau \neq 0$):

- If $e_1 = 0$ and $e_2 > 0$, then $\frac{\partial \bar{L}}{\partial e_1} < 0$ and $\frac{\partial \bar{L}}{\partial e_2} = 0$, such that $\text{MPE}_1 < \text{MPE}_2$.
- If $e_1 > 0$ and $e_2 = 0$, then $\frac{\partial \bar{L}}{\partial e_2} < 0$ and $\frac{\partial \bar{L}}{\partial e_1} = 0$, such that $\text{MPE}_1 > \text{MPE}_2$.
- If $e_1 > 0$ and $e_2 > 0$, then $\frac{\partial \bar{L}}{\partial e_1} = \frac{\partial \bar{L}}{\partial e_2} = 0$, such that $\text{MPE}_1 = \text{MPE}_2$.

The above rule states that fishermen will target the species that gives the higher MPE, or both species will be targeted if their MPEs are same. If $\lambda > 0$, the value of additional boat is positive and the fleet capacity constraint becomes binding; i.e., $e_i + e_{-i} = n$.

The optimal rule for $\tau = 0$, a special case, is slightly different from the above general rule. In this case only $\frac{\partial \bar{L}}{\partial e_1} = \frac{\partial \bar{L}}{\partial e_2} = 0$ can be satisfied, hence $e_i > 0, i = 1, 2$. Any effort allocation satisfying the fleet capacity constraint will be optimal, because every unit of effort is equally divided between two species. We consider $\tau = 0$ as a trivial case, hence the subsequent discussion will focus on the cases when $\tau > 0$.