ICES Journal of Marine Science Advance Access published March 16, 2016

ICES Journal of Marine Science

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

ICES Journal of Marine Science; doi:10.1093/icesjms/fsw031

Evaluating the benefits and risks of species-transformation provisions in multispecies IFQ fisheries with joint production

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Woods, P. J., Holland, D. S., and Punt, A. E. Evaluating the benefits and risks of species-transformation provisions in multispecies IFQ fisheries with joint production. – ICES Journal of Marine Science, doi: 10.1093/icesjms/fsw031.

Received 23 October 2015; revised 9 February 2016; accepted 9 February 2016.

Species-transformation provisions allow fishers to convert quota of one species to that of another species at prescribed conversion rates. These provisions, along with other catch-quota balancing mechanisms, are meant to aid fishers in matching available quota to actual catch so that incentives to discard are reduced. In this paper, we use a bioeconomic model to examine how species-transformation provisions affect sustainability and profitability of a multispecies fishery. We base parameterization of the model loosely on management of the Icelandic demersal fishery, which currently employs one of the broadest implementations of species transformations. To represent fisher behaviour in each year, effort is allocated among two or three métiers, such that total profit for that year is maximized. Each métier represents a combination of three species' catchability rates that define which species are targeted by each métier and how independent a species' catch rate is from that of other species. Assumptions regarding the degree to which fishers can target specific species by shifting effort between métiers, as well as how relative profitability among métiers varies, are paramount to understanding more generally how fishing regulations such as species transformations can be expected to change fishing patterns. This constraint depends not only on how strongly associated species catches are within a métier but also on relative species abundance and what alternate métiers are available.

Keywords: bioeconomic model, catch-quota balancing, fisheries management, individual fishing quotas, joint production, métier, short-term profit.

Introduction

The usefulness of individual fishing quotas (IFQs), which set output limits for either catch or landings, has been hotly debated for multispecies fisheries. In some cases, IFQ systems have controlled overexploitation (Costello *et al.*, 2008; Branch, 2009; Chu, 2009) and increased fishery value, profitability, and safety (OECD, 1997; NRC, 1999). Other cases show them to be ineffective without additional effort controls (e.g. Bastardie *et al.*, 2010; Toft *et al.*, 2011; Iriondo *et al.*, 2012) and may even aggravate a discarding problem when a species quota is filled before the quota of a more profitable species (Branch, 2009; Poos *et al.*, 2010).

As a result, most multispecies IFQ systems have "catch-quota balancing" mechanisms that add flexibility in balancing catches with quota, and reduce incentives to discard. For example, the ability to trade and lease individual transferable quotas (ITQs) is meant to enable fishers to acquire quota to cover catch for which they do not hold sufficient quota (Arnason, 2005). However, inefficient quota markets in multispecies ITQ systems can make it difficult or costly for fishers to obtain quota (Holland, 2013; Holland and Norman, 2015), especially when fishers are uncertain of their quota needs (Holland and Jannot, 2012; Holland and Norman, 2015 (For example, in the Pacific groundfish IFQ, several rockfish species with aggregate catches <50% of total quota have traded at prices well above the landed value of the fish. This suggests that fishers may have a substantial option value associated with holding quota that they may, but probably won't, need.)). Other catch-quota balancing mechanisms that may reduce incentives to discard include: (i) transferring unused quota to the following year or borrowing quota from next year to account for overages (between-year transfers); (ii) per unit fees for catch landed without quota; and (iii) the transformation of quota from one species into another at specified exchange rates (Holland and Herrera, 2006; Sanchirico *et al.*, 2006). Species transformations are particularly intriguing as they theoretically formalize a continuum from single-species management to multispecies management. Use of quota baskets that treat several species as a single quota stock can be considered to allow a 1:1 kg conversion among constituent species, whereas single-species management has 0:1 conversion ratios among all species. As a result, species quota-transformation provisions have broad applicability, but the benefits and biological risks of implementing them are not well understood.

We used a bioeconomic model based on the Icelandic management system to evaluate the utility and risks of species quota-transformation provisions, along with additional catch-quota balancing mechanisms included in this system. Iceland was one of the first nations to implement a management system that uses ITQs of a total allowable catch (TAC). Quotas are applied to catch, which is roughly similar to landings under a discard ban. ITQs were introduced for herring (*Clupea harengus*) in 1979 (Jakobsson and Stefánsson, 1999) and expanded to most Icelandic fisheries in 1991 (Arnason, 2005). Iceland currently employs one of the most extensive sets of catch-quota balancing rules, which include between-year transfers, species transformations, and some leniency in penalizing over-quota landings, along with quota trading. ITQs are transformed from one species to any other species within the demersal fishery except cod (*Gadus morhua*) and Norwegian lobster (*Nephrops norvegicus*) according to ratios of "cod equivalence", which are set according to relative market price during the previous year. Transformations are implemented as a fisher's quota is counted against his self-reported catch in a real time, on-line reporting system and is subject to certain limitations described in Methods.

Biological consequences of these catch-quota balancing mechanisms on the fished populations in Iceland appear to have been benign (Woods *et al.*, 2015a). However, these rules allow legal routes for exceeding quotas. Avoiding biological and economic risks of overexploitation depends on anticipating how the system will be used by fishers. In a previous study (Woods *et al.*, 2015b), we explored how this species-transformation system could be expected to function when fishers were maximizing their short-term profits and the underlying assumption of joint production among species was false (i.e. fishers could actually target individual species). The intent was to identify situations in which chronic over-quota landings could arise, so that such situations could be recognized and avoided when designing or monitoring fisheries with species-transformation systems implemented. The study showed that species transformations effectively removed any constraint of the TAC for some species, so any apparent adherence to a TAC must be based on either low profitability or bycatch rates that are balanced among species. Attempts to achieve maximum economic yield were, therefore, undermined.

We build on the prior study by focusing on potential benefits (as well as risks) of species-transformation systems under joint production, when fishers have limited ability to adjust the species mix. We constructed a theoretical bioeconomic model of a multispecies demersal fishery that includes age-structured population dynamics for three species, division of the fishery into two–three métiers that differ in catchability patterns among the species, a catch-quota balancing regime modelled directly on the Icelandic ITQ system, and a theoretically motivated representation of fishing behaviour that uses an optimization routine to allocate fishing effort among the métiers to maximize profit in each annual time step. We evaluated how basic attributes of the fishery affect results, such as how joint the production is or how disparate abundance levels are among species, as well as relative profitability among métiers. In Supplementary data, we also analysed whether management error implemented as a fluctuating regime could increase profitability (see Supplementary Section 3).

Métiers are used to represent fishery compartmentalization, so their generalized parameterization could represent a variety of mechanisms, such as differences in fleet segments, gears, or spatial patterns. Most models that include optimized effort allocation among métiers are intended to evaluate long- or mid-term consequences of different management strategies, such as how much effort each fleet segment should be allowed, given that total effort is constant (e.g. Hoff *et al.*, 2010; Punt *et al.*, 2011; Guillen *et al.*, 2013). However, the optimization step in our model is not constrained to produce effort values that fill TACs or sum to a predesignated total, but is based on short-term profit maximization. Therefore, it is strictly meant to represent economic fishing behaviour. Few models include such an optimization routine to evaluate management strategies or potential regulations (Prellezo *et al.*, 2012; Plagányi *et al.*, 2014; but see Little *et al.*, 2009; Poos *et al.*, 2010; Toft *et al.*, 2011; Thøgersen *et al.*, 2012), although such analyses may be useful for better understanding incentives generated by regulations and potential unintended consequences (Wilen *et al.*, 2002; Branch *et al.*, 2006; Grafton *et al.*, 2006; Fulton *et al.*, 2011).

Methods

Model description and parameterization

The bioeconomic model was coded and analysed using Matlab v. 8.1.0.604 and C and has four main components: (i) population dynamics, (ii) harvest-control rules, (iii) catch-quota balancing system, and (iv) economic environment. A technical appendix and notation list are given in Supplementary Sections 4 and 5.

Population dynamics

The three species—Atlantic cod, haddock (*Melanogrammus aeglefinus*), and lemon sole (*Microstomus kitt*) –included in the model were chosen to represent a wide variety of absolute abundance and market values (see Supplementary Sections 1.2 and 4.1 for further details). Haddock fetch a slightly lower price per kilogram than cod, whereas lemon sole fetch a slightly higher price, which is reflected in the "cod equivalent" (CE) values we used as conversion rates in the species-transformation system (1, 0.867, and 1.117, respectively). Information from recent stock assessments was used to parameterize age-structured population models for Atlantic cod and haddock (ICES, 2012, 2015; Anonymous, 2015; Björnsson, 2013), as was the only stock assessment available for lemon sole (Valtýsson, 1998; see Pálsson and Kristinsson, 2005 for updated weight and maturity data). Biomass levels resulting from population dynamics models influence the economic environment within an annual time-step by changing the outcome of the management system (i.e. harvest-control rules and catch-quota balancing regulations), as well as the profitability of fishing individual species (i.e. it is more costly to fish species with overfished biomass levels) (Figure 1).

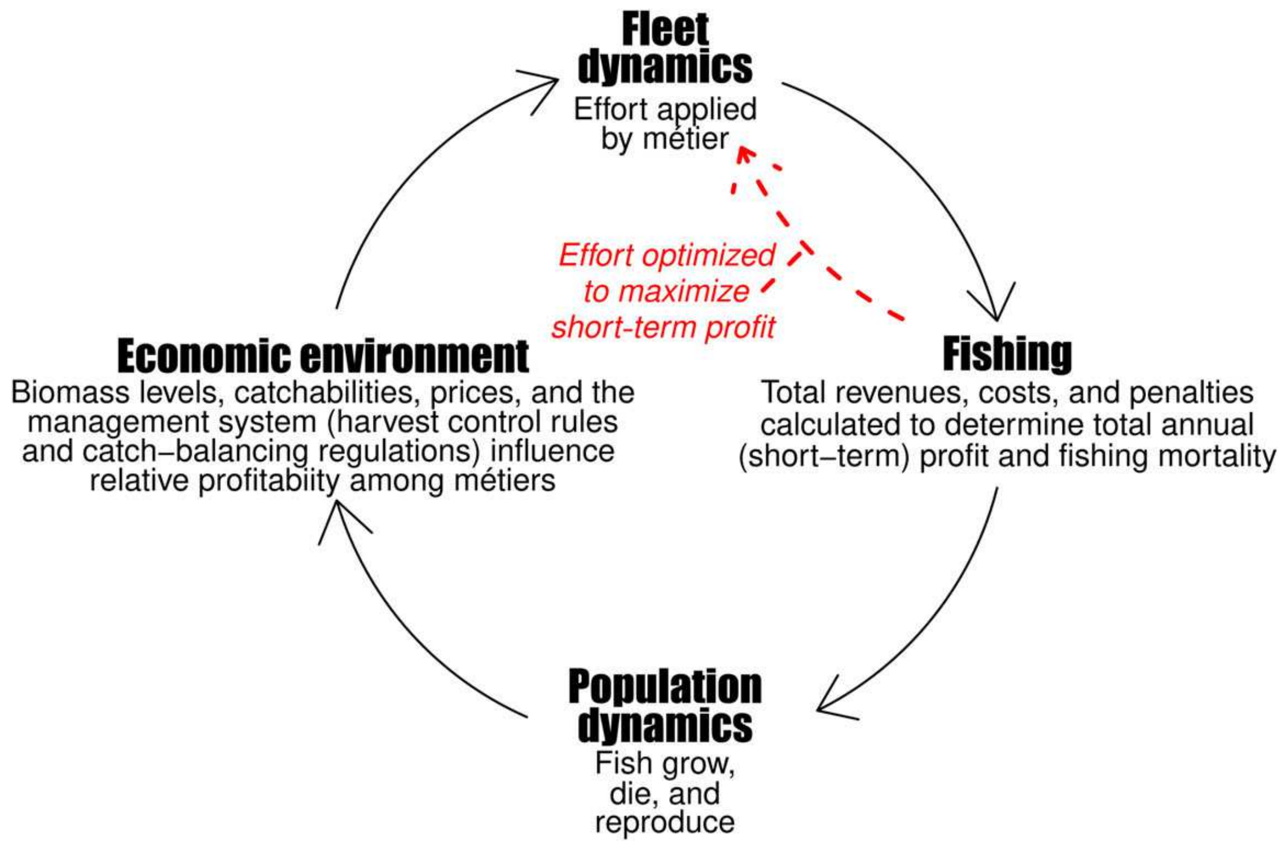

Figure 1. Conceptual model diagram within an annual time step. Population dynamics, the management system, and the time-invariant catchabilities and prices present an economic environment generated last year, to which this year's fleet dynamics (beginning at the top) respond by fishing according to a short-term, profit-maximizing algorithm (dashed line), thereby resetting the economic environment present at the end of this year. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

Harvest-control rules

It was assumed that managers have perfect information about stock status and set next year's TAC using species-specific harvest-control rules. In both the model and reality, cod and haddock are managed using harvest-control rules designed to yield approximately a 20 and 40% harvest rate (as a percentage of reference biomasses, see Supplementary Sections 1.2 and 4.2). When all TACs were filled under equilibrium, fishing yielded slightly less than maximum sustainable yield (MSY) for cod and ca. MSY for haddock. Therefore, biomass in this equilibrium ($B_{\mathrm{TAC,s}}$) slightly exceeded $B_{\mathrm{MSY,s}} = 1\,074\,700$ t for cod and roughly equalled $B_{\mathrm{MSY,s}} = 134\,900$ t for haddock. Lemon sole is managed via $F_{\mathrm{MSY,s}}$ in the model, yielding $B_{\mathrm{MSY,s}} = B_{\mathrm{TAC,s}} = 12\,500$ t. All results pertaining to biomass levels are shown in relation to $B_{\mathrm{TAC,s}}$.

Catch-quota balancing regulations

We assumed that trade occurs in an optimally efficient market, so that we can represent the industry as a single entity controlling multiple vessels in a way that maximizes profits. Thus, we modeled only aggregate whole-industry, rather than vessel-specific, catch and catch balancing. Three catch-quota balancing mechanisms were implemented in the model in a way that is consistent with the actual operation of the Icelandic system. In order, these were (i) between-year transfers, (ii) species transformations, and (iii) a "grace take" provision. Up to 5% of quota may be landed as "grace take", for which 20% of revenues from landings are kept by the fishers and 80% ceded to authorities. Landings beyond these are forfeited to the government in reality; however, we implemented an additional fine by removing 150% of the illegal take revenue, the additional 50% of which is meant to represent additional disincentives for exceeding quota (e.g. fishing license suspension and possible revocation).

In our model and in practice, species transformations are automatically implemented: the fisher has no choice regarding which species quota can be used to cover which species catch, so that quota is transformed from all species with excess quota. A full list of limitations can be seen in Supplementary Sections 1.2 and 4.3, but the limitations that are the most important for understanding results are: (i) no quota can be transformed into cod quota, although cod quota can be used to generate quota for other species and (ii) no $>$1.5% of the total quota available at the start of the fishing year (summed across species in CE) can be transformed into a single species.

Economic environment

Within each model run, age- (a), and species-specific (s) selectivity ($\sigma_{s,a}$, see Supplementary Section 4.4, for all equations containing variables in this component), species- (s), and métier-specific (m) catchability ($c_m q_{s,m}$), and species price (φ_s) remained constant through time (t), affecting relative profitability of métiers and consequently biomass levels (Figure 1). Relative profitability affects fleet dynamics by changing how effort would be most profitably allotted to métiers, and, therefore, profit gains from fishing (Figure 1). Métier-specific effort varied through time ($\xi_{t,m}$) as a result of optimizing effort within annual time-steps to maximize annual short-term profit for the industry as a whole: as a total across species and métiers.

Métier-specific efforts generated each year are unconstrained, but are nonetheless interdependent because the species-transformation system effectively removes some of the penalties for surpassing a TAC for some fisheries, depending on how heavily others are targeted. The effort being applied to any métier is, therefore, a function of the métier catchability pattern that defines joint production (i.e. the combination of species- and métier-specific catchabilities relative to each other) and past fishing that affects current biomass. We equate effort allocations to fleet dynamics in our model, although, in reality, métiers can arise from a variety of mechanisms beyond fleet dynamics, as catchabilities can change with gear type, fishing location, depth, towing speed, etc. In addition, effort allocations in the model are not constrained by fleet capacity or limitations to enter or leave the fishery (i.e. there is no cost to moving effort between métiers).

Within each year, fishing mortality was calculated as the product of nominal effort by métier (generated endogenously as described above), species age-specific selectivity, and species- and métier-specific catchability. The Baranov catch equation was used to calculate catches, after which annual total profit, summed over species and métiers, was composed of total revenues less fishing costs and penalties in the form of lost revenues and fines from grace take and illegal catch. Prices did not vary over time or with level of catch, reflecting an assumption of perfectly elastic demand. Prices and the CE conversion rates equalled each other ($\varphi_s = \gamma_s$), reflecting an assumption of accurately observed relative gross value among species.

Costs were linearly related to total, and parameterization was based on the assumption that operational costs appear to fluctuate close to 75% of revenues, which is consistent with recent history of the fishery (Woods *et al.*, 2015b). We used an iterative procedure to determine a linear cost coefficient that fits this criterium for each unique set of métiers, described in Supplementary Section 1.3.

Model analyses

Métier patterns, species independence, and catch patterns

Defining "métiers" in fisheries science is a way by which diverse fishing activities can be simplified into a few homogenous categories often defined by fishing vessel, gear type, and target species, especially so that partial fishing mortalities can be more accurately quantified (Deporte *et al.*, 2012). In this study, we treat métiers as hypothetical fishing activity options that are predefined by a set of métier- (m) and species-specific (s) catchabilities that are constant through time and independent of species abundance ($q_{s,m}$, Supplementary Section 4.4).

Many unique sets of catchabilities can be imagined for the three species, in which every métier has at least one species with higher catchability than other species. To aid discussion, we define species with a higher catchability than other species within a métier as the "target" species of a métier, as this higher catchability allows the métier to favour catch of the target species. Our use of "target" does not correspond directly with the standard use of "target," which refers to the species in a catch that yields the greatest economic gain. Since economic gain is an emergent property of our model, the standard definition is not useful here.

In the simplest base case, catchability values are equal among métiers, but set by species to achieve a ratio that would enable fishing all TACs exactly in equilibrium. We defined different target species among métiers, then raised catchability of target species within all métiers by a constant factor, so that the ratio in catchability between target and non-target species remained symmetrical across métiers. Which species are chosen to be target vs. non-target species, therefore, defines the "métier pattern, " whereas the catchability ratio between target and non-target species defines its "species independence," reflecting a degree of targetability. Fishing a métier pattern at a given level of species independence then results in an equilibrium "catch pattern", which depends on how each métier was actually used (i.e. how effort was distributed among métiers at equilibrium, which we refer to as the "fishing pattern" that defines fleet dynamics).

Exploratory analyses led us to focus on three basic types of métier patterns (Figure 2), and we increased catchability of target species by a multiple of 3, 8, or 9998 to represent low, medium, and high levels of species independence. The first pattern we analysed had a single-target species for each métier (P0, Figure 2). Species independence level 3 (i.e. limited targeting) translates to obtaining $1/(1 + 1 + 3) = 20\%$ of the target species catch from each of the two non-target métiers vs. $3/(1 + 1 + 3) = 60\%$ from the single-target métier, assuming effort is equal among métiers. For level 8 (i.e. substantial targeting), 10% vs. 80% would be obtained. For level 9998 (i.e. near-perfect targeting), 0.01% vs. 99.98% would be obtained from the two non-target vs. the single-target métiers, effectively representing a fully non-joint fishery. The other two patterns only included two metiérs, one of which targeted two species simultaneously,

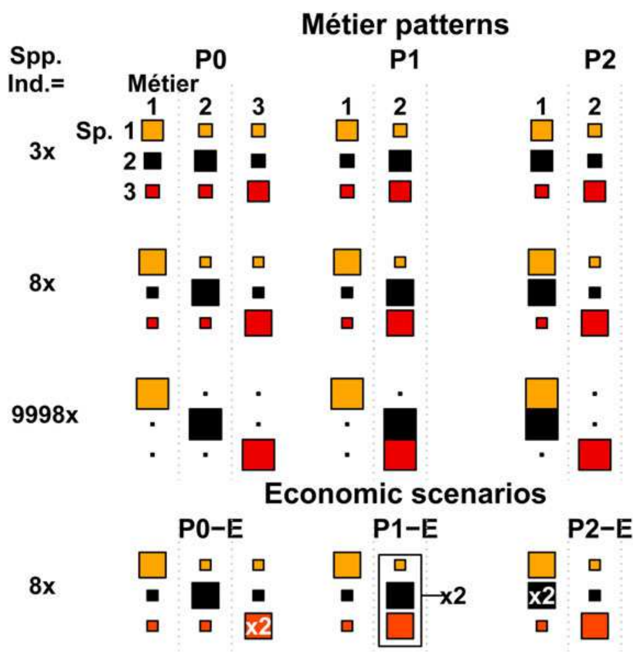

Figure 2. The top section shows the three métier patterns analysed (P0 – P2) at each species-independence level (species independence = 3 – 9998x). Each square represents the increase in catchability of a target species (large boxes) in relation to non-target species (small boxes) as a multiple of the base-case species catchabilities (i.e. those needed to fish all TACs at equilibrium simultaneously). The bottom section shows the three economic scenarios analysed (P0-E – P2-E) at a species-independence level of 8x. The "x2" markings refer to doubling catchabilities of either target species (P0 and P2) or entire métiers (P1) to invoke an imbalance in revenue per unit effort at the start of a model run. Species 1 – 3 represent Atlantic cod, haddock, and lemon sole, respectively. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

indicating highly joint production (P1 and P2, Figure 2). Because two target species occur on one métier, they cannot represent fully non-joint fishing. Preliminary analyses indicated that these three patterns generally captured similar dynamics as many more complex patterns.

Equalizing RPUE among métiers

Catch among métiers is equal at a species-independence level of 1×, but as species-independence level increases, métiers that target high-biomass species produce larger total catches than others at the same effort level. Consequently, maximizing short-term profit would cause effort to focus on the métier that targets high-biomass species, assuming prices of the other species are not high enough to compensate for catch from a smaller biomass. If métiers that produce very different quantities of total catch are to coexist, they must have roughly similar levels of relative profitability; otherwise they would never be observed simultaneously. Therefore, we assumed that the métiers producing low total catch are relatively inexpensive to fish by setting a higher catchability for all species in that métier. To do this, at the beginning of a model run, we first allowed fishing to occur such that all TACs (i.e. the levels allowed by harvest-control rules and between-year transfers) are filled at equilibrium and biomass is at $B_{TAC,s}$ for all species. We then used the métier pattern to assign a portion of each species catch to each métier, assumed that effort was equal among métiers, then calculated RPUE as the total métier-specific revenue divided by métier-specific effort. These RPUE values were then equalized across métiers by setting a catchability correction parameter c_m to modify the amount of effort needed to fish an individual métier ($t = 0$, Supplementary Section 4.4, Equation 20). The relative catchabilty of the target species thus remains 3, 8, or 9998x that of the other species within a métier, but the entire vector of a métier's catchabilities in relation to other métier's catchabilities is multiplied by c_m.

Economic scenarios

Effort allocation among métiers in a given year depends on the economic environment (i.e. biomass levels, métier, and price parameterizations) and the penalty structure invoked by the management system. In this study, we generated changes in the economic environment by manipulating the métier pattern ($q_{s,m}$, Supplementary Section 4.4) in year 0 after the initial parameterization that had equalized RPUE across métiers, so that some species and/or métiers would generate greater RPUE, at least during the initial years of the model run. An increase in catchability of a single species affects the symmetry in catchabilities of target to non-target species, forcing fishing to occur at a faster rate due to a higher catch per unit effort. Alternatively, when the catchability of an entire métier is increased, the pattern of catchabilities remains, so that all TACs may be filled simultaneously at equilibrium under the corresponding set of effort values. In both cases, however, increasing catchability will also decrease the cost for fishing the métier on which it was raised, leading to greater fishing effort in the short-term. In reality, this could occur, for example, with environmental changes leading to species aggregation, with changes in processing or the marketplace, or with the generation of new métiers due to competitive or regulatory exclusions from other métiers.

We focus our analysis on three economic scenarios that have contrasting properties (Figure 2): P0-E—métier pattern P0 with lemon sole catchability doubled in its target métier, P1-E—métier pattern P1 with métier 2 catchability doubled, and P2-E—métier pattern P2 with haddock catchability doubled on its target métier. Doubling of catchabilities was chosen arbitrarily as a high enough level that would generate obvious usage of species transformations, but not be completely unrealistic. The realistic levels of relative abundance indicated by stock assessments that we use are highly imbalanced, so for comparison, we also present a fictional scenario in Supplementary Section 2, in which the effect of differing species abundance was neutralized by dividing catch by MSY.

Within a single model run, the model was initialized by applying a métier pattern and species-independence level, equalizing RPUE, determining the cost parameter, then applying the economic scenario. Fishing then occurred according to effort allocations determined by short-term profit maximizations, with no species-transformation regulations implemented. After a steady state was reached, species-transformation regulations were implemented in year 101, and the steady state was analysed after 50 more years of fishing.

Results

Métier patterns, species independence, and catch patterns

We begin by presenting results from two simple, but contrasting, model runs. First, we consider métier pattern P0 at the three species independence (Figure 3). For P0, catches change slightly at

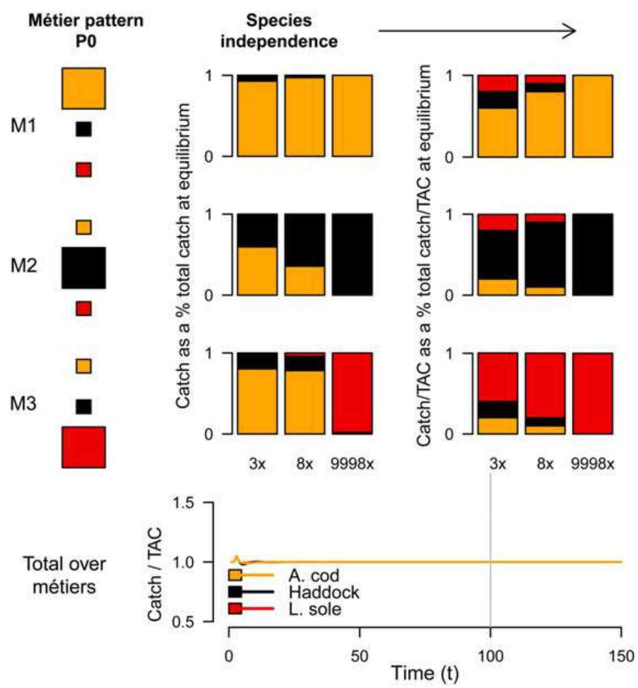

Figure 3. In barplots, catch results are shown for métier pattern P0 in three model runs that differ by species-independence level. The métier pattern is shown left, with larger boxes representing higher catchability of the target species relative to smaller boxes of non-target species. The first set of results represent the proportion of total catch obtained from each métier in a steady state (left panels), and the second set show the same, but with the effect of different stock abundance and harvest-control rules removed by dividing by the TAC expected while fishing the stock at equilibrium. The time-series shows results of total catch, summed over métiers, in relation to the TAC that would occur while fishing at equilibrium (all lines overlap). The first 100 years were implemented with no species transformations, followed by fishing with species transformations in place starting at $t = 101$ for another 50 years (after the grey vertical line). This figure is available in black and white in print and in colour at ICES Journal of Marine Science online.

$t = 1$ due to shifts in RPUE as the short-term profit maximization changes effort values, and settle at steady-state total catch levels that fill the TACs even after the introduction of species transformations (Figure 3, bottom panel). Cod often contributed the largest portion to steady-state P0 catch due to its high abundance (Figure 3, left barplots), although the proportion of its own catch attributed to each target métier still corresponded to species-independence level (Figure 3, right barplots). The same occurs for all species-independence levels for all base-case métier patterns, but with different catch patterns, indicating that symmetrical catchability distributions and how "clean" the fishing was (defined by species independence level) have no effect on total catch as long as all métiers are equally profitable in the short term.

Next, we consider a single métier (fully joint production) with a higher catchability of haddock relative to other species (Figure 4). In contrast to the scenario above, two equilibrium states may result depending on penalty rates: either (i) all TACs are either filled or overfilled, because the total penalties gained do not outweigh the additional revenues—costs (Figure 4a, penalty rate = 1.5× price) or (ii) at least one TAC remains partially unfilled because the penalties incurred outweigh the additional revenues—costs (Figure 4b, penalty rate = 3× price). As a result, asymmetrical catchabilities along with penalty rates may have an important influence on how heavily individual métiers are fished.

Economic scenarios

The métier patterns for P0-E and P2-E are asymmetrical due to the doubling of a single species catchability and are, therefore, more likely to be more sensitive to the trade-off exemplified in Figure 4, as well as reductions in penalties caused by species transformations. Our study generally supports this idea, and also demonstrates important differences among asymmetrical patterns.

In the first scenario (P0-E), a cyclical pattern of high and low lemon sole catch (Figure 5a–c), resulting in decreased biomass levels (Figure 5d–f) occurred from effort being shifted mainly between métiers 2 and 3 (Figure 5g–i) due to a difference in RPUE before species transformations were introduced (Figure 5j–l). Greater targeting of the high-value métier led to a reduction in RPUE after the implementation of species transformations, so that RPUE values become more equal in the steady state, but may not be exactly equal due to the boundaries of management limitations, which define when penalties would start to incur (Figure 5j–l). Cyclical patterns did not appear to dampen or heighten over time (see Supplementary Section 1.4). In peak years, species-transformation limitations allowed lemon sole catch to exceed its TAC by a large percentage because the lemon sole TAC contributes a small proportion to the total sum over species TACs, on which the definition of species-transformation limitations are based (1.5% of the total quota, see limitation ii in Model description).

When catchability for an entire métier was increased, as was done for P1-E (métier pattern P1 with métier 2 catchability doubled) (Figure 6), species-independence levels were important in determining the balance in profitability between two métiers, and whether a second métier was used. For P1-E, only a single métier was fished at a low species-independence level due to high relative RPUE before and after the introduction of species transformations (Figure 6a, d, g and j). At medium species-independence levels, the introduction of species transformations caused cod quota to be transformed into lemon sole and haddock quota (Figure 6b, e, h and k), because directing more effort toward métier 2 slightly reduced costs. As a result, catch was increased for lemon sole and haddock, but decreased slightly for cod over the first 5 or so years after the introduction of species transformations. In contrast to P0-E, overfilling the lemon sole TAC was limited by the constraint of species transformations on haddock, because haddock and lemon sole were caught at the same rate. At high species-independence levels (Figure 6c, f, i and l), essentially no cod can be obtained

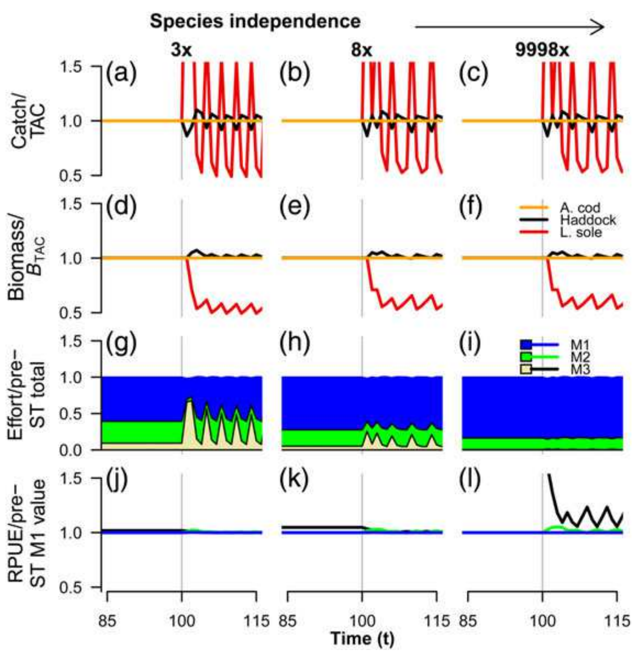

Figure 5. Model results of catch and biomass are shown by species relative to TAC and biomass expected when fished under the harvest-control rule at equilibrium (B_{TAC}), respectively, for economic scenario P0-E for the three species-independence levels 3x, 8x, and 9998x (a–f). Effort and RPUE by métier are also shown (bottom two panel rows) relative to the total effort and the RPUE in métier 1, respectively, during the year before species transformations (j–l) introduction (year 100, solid grey vertical bar). Lemon sole catch increased and biomass decreased with the introduction of species transformations under all species-independence levels due to its high catchability in métier 3 (a–f), which caused a higher RPUE (j–l) and consequently a greater shift in effort toward fishing métier 3 (g–i). This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

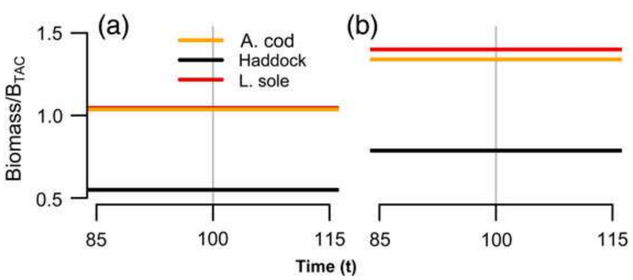

Figure 4. Model results of biomass over that expected when fishing the harvest-control rule at equilibrium (B_{TAC}) showing the effect of penalty rates on a fully joint-production scenario: a single-métier fishery in which haddock must be fished at 2x the catchability of lemon sole and cod. The penalty rate for catching over-quota fish is set at 1.5x the species price for panel a, and 3x the species price for panel b. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

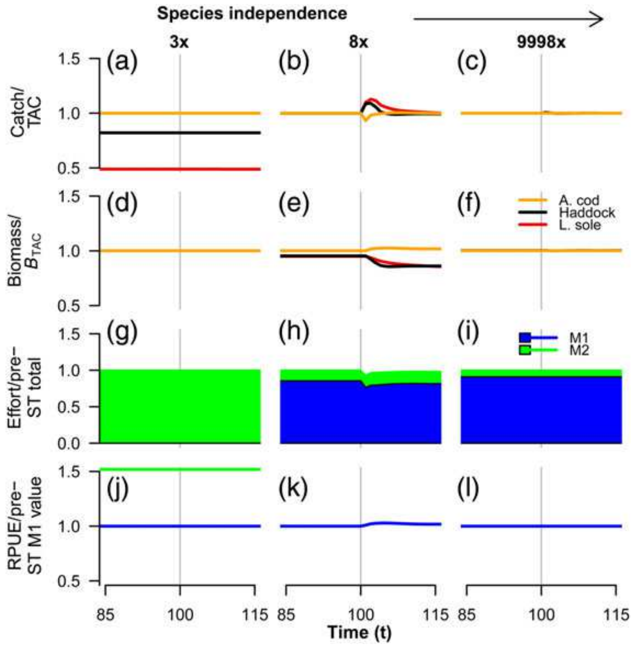

Figure 6. Model results of catch and biomass are shown by species relative to TAC and biomass expected when fished under the harvest-control rule at equilibrium, respectively, for economic scenario P1-E for the three species-independence levels 3x, 8x, and 9998x (a–f). Effort and RPUE by métier are also shown (bottom two panel rows) relative to the total effort and the RPUE in métier 1, respectively, during the year before species transformations (j–l) introduction (year 100, solid grey vertical bar). Haddock and lemon sole biomass levels are $<0.5B_{TAC}$ in (d) and not shown. The solid grey vertical bars mark year 100, the year before the introduction of species transformations. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

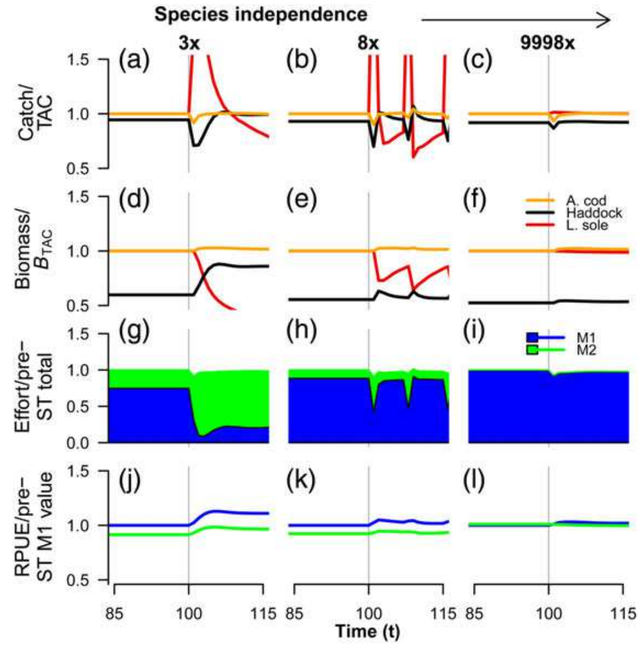

Figure 7. Model results of catch and biomass are shown by species relative to TAC and biomass expected when fished under the harvest-control rule at equilibrium, respectively, for economic scenario P2-E for the three species-independence levels 3x, 8x, and 9998x (a–f). Effort and RPUE by métier are also shown (bottom two panel rows) relative to the total effort and the RPUE in métier 1, respectively, during the year before species transformations (j–l) introduction (year 100, solid grey vertical bar). Lemon sole catch increased and biomass decreased with the introduction of species transformations under all species-independence levels due to its high catchability in métier 3 (a–f), which was caused by a higher RPUE (j–l) and consequently a greater shift in effort toward fishing métier 3 (g–i). This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

using the second métier. At the higher two species-independence levels, the balance in métier usage is determined by relative profitability rather than limitations of the management system, so RPUE are equal among métiers (Figure 6j–l).

Economic scenario P2-E (métier pattern P2 with haddock catchabily in métier 1 doubled, Figure 7) represents a situation in which fishing a less profitable species (haddock or lemon sole) restricts fishing of a highly profitable species (cod) because the less profitable species TAC fills faster due to a relatively higher catch rate. Before the introduction of species transformations, cod TAC is slightly underfilled (Figure 7a–c), as haddock penalties and costs outweigh cod revenue, resulting in biomass slightly greater than $B_{TAC,s}$ for cod and biomass less than $B_{TAC,s}$ for haddock (Figure 7d–f). Cyclical catch patterns did not appear to dampen or heighten over time (see Supplementary Section 1.4). At the lower species-independence levels, a large decrease in penalties drove a shift toward utilization of métier 2, with the introduction of species transformations (Figure 7g and h), despite a slight increase in cost and decrease in revenues. This shift allowed biomasses of both cod and haddock to increase slightly after the introduction of species transformations (Figure 7d and e), thereby increasing RPUE for both métiers (Figure 7j and k). A constant difference in RPUE levels persisted between métiers because relative profitability was mainly determined by penalties accrued after management limitations were met. At the highest species-independence level, however, the small quantity of cod obtainable from the second métier would have caused a larger reduction in revenue, outweighing the benefit of such a large shift (Figure 7c, f, h and k). Therefore, in this example, there is a primary trade-off within métiers between greater revenues vs. penalties gained when fishing one species to its TAC (cod) requires overfishing another species on the same métier (haddock on métier 1, lemon sole on métier 2), as well as a secondary trade-off between how much effort should be allotted to each of these less-than-ideal choices.

Discussion

This study was designed to show how the emergent catch patterns that result from a known pattern of catchabilities within and between métiers are affected by fisheries regulations that allow species transformations of quota. The study demonstrates that métier patterns, relative species abundance, and relative profitability can have important impacts on how species transformations are used and whether they lead to overfishing of some species.

Influence of métier pattern and species independence on catch patterns

In general, there are three aspects of the metiér pattern that strongly influence how catch patterns develop. The first is flexibilty in the métier pattern—whether there are enough options to allow targeting of each species. We define a highly "constrained" fishery as one that has few options and an asymmetrical catchability pattern, thereby requiring a higher catch rate of one species to fill the TAC for another species, possibly leading to long-term overutilization of the first species. Symmetrical patterns, on the other hand, allow constant fishing levels to fill (and not surpass) all TACs simultaneously regardless of species-independence level. However, when the métier pattern was only mildly asymmetrical and there were enough different options, each of which were profitable enough to utilize, even at low species-independence levels, it was still possible to achieve catches very close to filling the TACs without introducing species transformations (Figure 5). Whether it was possible to fish "cleanly" was less important than the availability of different fishing options. Therefore, if reducing the constraint of a fishery is the main goal of a regulation, increasing viable options available to fishers may help achieve this, potentially by reducing access or gear restrictions (Kasperski and Holland, 2013; Hentati-Sundberg *et al.*, 2015) or by encouraging a wider variety of consumer choices and subsidizing opportunities to switch target fisheries (Garnacho and Pinnegar, 2013; Witkin *et al.*, 2015). Fishing diversification has the additional benefit of decreasing risk associated with environmental or market variability (Kasperski and Holland, 2013).

The second important aspect is whether there are any constraining species on the most profitable métier, and if so, how constraining they are. That is, just because there may be a variety of métiers providing flexibility in choice, the effort levels needed to use all simultaneously may be too costly. The presence of alternate métiers is not sufficient to ensure that a constraining species on the most profitable métier will not be overutilized. Our results indicated that the level of constraint had strong consequences for how heavily that most profitable métier was fished (P1-E and P2-E, Figures 6 and 7). In the most extreme case, only a single métier was fished at the lowest independence level (Figure 6), because sufficient low-cost cod were obtained from métier 2 making it worth catching haddock and lemon sole over their TACs, leading to the facade of a constrained fishery. In these cases, regulatory measures could be used to reduce the relative profitability of the most profitable métier (heavy fines or other penalties); however, species transformations do not appear helpful as they generally reduce penalties.

The third key aspect is the relative profitability of the different métiers, and which species are driving overall profitability. How heavily the most profitable métier is fished, and the constraints that control it, have knock-on effects for how heavily secondary métiers are fished. Using a regulation to shift penalties away from profitable métiers will likely cause effort to shift toward other métiers. This shift could require overfilling another TAC (P2-E, Figure 7), or all TACs may be filled simultaneously (P0-E, Figure 6). Predicting such knock-on effects requires an understanding of how profitable alternate métiers are, and why. A shift in effort due to penalties would also likely require an increased total cost, but, at least theoretically, this could be weighed against the long-term benefits of increasing the biomass of an overfished species. Although seemingly obvious, this simple result is potentially one of the most misunderstood factors when regulations bring about unexpected changes in fisher behaviour (Wilen *et al.*, 2002; Branch *et al.*, 2006; Grafton *et al.*, 2006; Fulton *et al.*, 2011).

Simple, yet substantial, effect of relative abundance on fishing patterns

The need to understand relative profitability of métiers and species driving that profitability reveals the simple, yet substantial, effect of relative abundance on fishing patterns. Highly abundant species accrue penalties and revenues at a faster rate than low-abundance species (assuming a similar catchability), thereby outweighing the effects of changes in profitability of lower-biomass species as effort shifts among métiers. In our study, in which abundance was highly, but realistically, imbalanced, whether a métier was used depended on how much of the high-abundance species was caught. This meant fishing dynamics were almost entirely controlled by the priority to fill the cod TAC, even if it required overfilling two other TACs (P1-E, Figure 6).

A hierarchy of biomass was, therefore, established, prioritizing catching the cod TAC even if it required catches of haddock or lemon sole beyond their TACs. Next, the haddock TAC was caught, even if it means under- or overcatching lemon sole. Finally, lemon sole TAC was filled exactly only if there were no other limitations. Overfilling a lower-biomass species TAC would only be deterred if total penalties offset the additional revenues or cost reduction generated from catching more of the higher-biomass species. When abundance is highly imbalanced, the effect of any regulations intended to change fishing that rely on relative price (e.g. fines, taxes) pale in comparison with the potential effect of relative abundance on relative profitability, so fine rates would need to be immense. Instead, the incentive to discard or land fish illegally is likely to increase with such extreme fine rates as fishers lose faith in the fairness of the system (Sutinen and Kuperan, 1999). Other mechanisms, such as peer pressure or spatial management, which change catchability patterns, are needed. In addition, if the fisheries policy aims to deter overfishing low-biomass species with species transformations in place, then additional safety mechanisms or alternate designs of the species-transformation system should be considered. In this light, in Iceland, it is more likely that the requirement to stop fishing until quota for over-quota species has been acquired, and the risk of losing licensure, are greater disincentives to surpassing TACs than fine rates. As cod TACs are most often filled consistently in the Icelandic fishery (Woods *et al.*, 2015b), and assuming there is very little illegal fishing or discarding in the fishery (Pálsson *et al.*, 2015), there is also likely enough regulatory flexibility and diversity of target strategies (métiers), that other species are not consistently overfilled to fully harvest cod TACs.

Despite the inherent risks to overfishing low-abundance species in a system similar to one modelled here (Figure 3 and Woods *et al.*, 2015b), the métier structure may actually offer some protection in certain cases, even when species transformations are implemented. First, as discussed earlier, it must be emphasized to recall that the presence of high bycatch does not necessarily reflect a constraint: high targeting despite high bycatch is possible and unintuitively represents non-joint production. Ignoring bycatch levels then, in cases where there are fewer options for targeting species individually, and the catchabilities of a low-abundance species are correlated with a higher-abundance species so that their TACs are filled at a similar rate, the low-abundance species will be additionally protected by constraints on fishing the more-abundant species. For example, the necessity of catching lemon sole at the same rate as haddock for P1-E decreased its vulnerability to being highly overfished (Figure 6). That is, instead of lemon sole biomass being vulnerable to unpenalized catch levels that are 360% of its TAC due to species-transformation limitations, it is only vulnerable up to the same level that haddock is vulnerable—109% of its TAC (see second limitation in Methods). Any species highly correlated with cod at a similar catchability could not be overcaught because cod was excluded from the system, although even if it were included, it could only be fished to ca. 101% of its TAC. Perhaps this is an alternate reason the species-transformation system, as implemented in Iceland, has not historically led to consistently overfilled TACs for low-abundance species (Woods *et al.*, 2015a), although supporting this hypothesis would require considerable detailed knowledge.

Difficulty in categorizing a real fishery

Although our results indicate that distinguishing and quantifying métier patterns appears key in understanding how the implementation of a regulation will affect fishing patterns, this task is extremely challenging in reality without historical estimates of biomass levels and spatial distributions of that biomass, which would allow for better estimation of catchabilities. In addition, unreported discarding can affect interpretation of current fishing patterns by obscuring the relative profitability of a discarded métier as well as how frequently it is encountered. If the design of fishery regulations is to be improved, there is a strong need for development of methods to better characterize the structure of relative catchabilities occurring within a fishery.

In addition, understanding how flexible the fishery actually is or what options are available to fishers beyond the subset of possible métiers currently utilized the most can strongly affect outcomes. Interpreting patterns of catch without knowledge of how flexible the fishery actually is can lead to a false assumption of a strongly joint production in the fishery, when in fact other outcomes were possible, perhaps with minimal additional cost. In reality, as in our model, catch patterns from a métier are not observed when it is not fished, nor is it possible to quantify the unfished métier's profitability. Furthermore, placing too much emphasis on how much of one species is caught with another in an individual métier, instead of what alternate métiers are available and profitable enough to fish, can lead to a false assumption of a highly constrained fishery. For example, standard métier analyses are extremely useful for characterizing the multispecies nature of a fishery by simplifying correlational structure among species landing profiles using a combination of PCA, clustering, and discriminant analyses (Deporte *et al.*, 2012). However, to place métiers within an economic context, quantifying how much of the total fishery can be attributed to each axis, or by how much individual métiers overlap each other, is an important next step. This context is necessary to understand, for example, how much effort is currently allocated to fishing individual métiers (e.g. Russo *et al.*, 2011; Anderson *et al.*, 2012), the relative profitability of fishing individual métiers (e.g. Davie *et al.*, 2015), or how constrained a fishery is and the incentives generated by possible regulatory actions (e.g. Batsleer *et al.*, 2013).

Conclusions

Overall, the utility of a species-transformation system, as depicted here, depends on the goal of management. If management goals focus on maximizing whole-system profit, then disregarding risks to low-biomass species makes sense if it restricts optimal utilization of high-biomass species. Instead, if management goals include maintaining biomasses of all species above a certain limit, then species transformations may not aid management unless (i) the fishery is highly unconstrained and there is no "highly profitable low-abundance" species (see Supplementary Section 2 for example); (ii) low-abundance species are highly correlated with more highly abundant species and caught at overall sustainable rates across the entire fishery (as in P1-E, Figure 6); (iii) there is sufficient regulatory and market flexibility and target species diversity among vessels to prevent targeting of any species whose TAC can be substantially exceeded (although monitoring would be needed to ensure continuation of these conditions); or (iv) further regulations are implemented that discourage targeting species for which a vessel has no quota (as is done in Iceland, Woods *et al.*, 2015b). If the risk of overfishing low-abundance species is sufficiently controlled via the above or other mechanisms, then a species-transformation system may yield potential additional benefits, such as increasing flexibility for fishers to respond to environmental or market variability, building trust between fishers and managers, reducing enforcement burden for exceeding quotas, and reducing discards.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Acknowledgements

The preparation of this paper has been supported by the US National Science Foundation under Award No. OCE-1323991 and by the Norden Top-level Research Initiative sub-programme 'Effect Studies and Adaptation to Climate Change' through the Nordic Centre Centre for Research on Marine Ecosystems and Resources under Climate Change (NorMER). We also thank two anonymous reviewers for helpful comments on an earlier version of this paper.

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Handling editor: Emory Anderson