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Original Article

Risks and benefits of catching pretty good yield in multispecies mixed fisheries

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Multispecies mixed fisheries catch ecologically interacting species with the same gears at the same time. We used an ensemble of size-based multispecies models to investigate the effects of different rates of fishing mortality (*F*) and fleet configurations on yield, biomass, risk of collapse and community structure. Maximum sustainable yield (MSY) and F_{MSY} for 21 modelled species' populations in the North Sea were defined at the Nash equilibrium, where any independent change in *F* for any species would not increase that species' MSY. Fishing mortality ranges leading to "Pretty Good Yield" (*F*-PGY), by species, were defined as ranges yielding $\geq 0.95 \times$ MSY. Weight and value of yield from the entire fishery increased marginally when all species were fished at the upper end of *F*-PGY ranges rather than at F_{MSY}, but risk of species' collapse and missing community targets also increased substantially. All risks fell markedly when fishing at the lower end of *F*-PGY ranges, but with small impacts on total fishery yield or value. While fishing anywhere within *F*-PGY ranges gives managers flexibility to manage trade-offs in multispecies mixed fisheries, our results suggest high long-term yields and disproportionately lower risks of stock collapse are achieved when $F \leq F_{MSY}$ for all component stocks.

Keywords: community, ensemble, indicator, management, mixed-fishery, model, multispecies-fishery, North Sea, technical interaction, uncertainty.

Introduction

The concept of Pretty Good Yield (PGY), as credited to Alec MacCall and described and investigated by Hilborn (2010, 2011) suggests that a broad range of fish population sizes and by inference or analysis, rates of fishing mortality *F*, often produce yields that are similar to the theoretical maximum sustainable yield (MSY) achieved by fishing at F_{MSY}. Defining the proportion of MSY that is "pretty good" is to some extent arbitrary, but yields of 80–95% of MSY are often deemed PGY (ICES, 2015). The justification for the PGY concept is effectively demonstrated by outputs from many population assessments, which produce relatively flat-topped yield curves (relationships between predicted yield *Y* and *F*; Hilborn, 2010), meaning that a broad range of fishing mortalities can result in yield close to MSY.

In any fishery, and especially in a mixed-fishery where there are technical interactions (different populations caught at the same time by the same fishing gear) and multispecies interactions (where population abundances influence each other through predation and competition), it is challenging or impossible to fish all populations (in practice, stocks) at their individual F_{MSY} at the same time. This is because it is technically or ecologically impossible to allocate *F* among stocks in such a way that all stocks are fished at a safe and productive level simultaneously (Hollowed *et al.*, 2000; Vinther *et al.*, 2004; Ulrich *et al.*, 2011, 2017). Further, fishing every stock at an F_{MSY} based on single-species considerations may compromise biomass reference points for some stocks given multispecies interactions. It may also lead to fishery-wide outcomes for weight of yield, value of yield, profitability, employment or state of the environment that are not expected or desired by the fishing industry, managers, politicians and other groups with an interest in fishery performance and impacts (Worm *et al.*, 2009; Dichmont *et al.*, 2010; Jennings and Rice, 2011; Salomon *et al.*, 2011).

The *F* selected to catch PGY from a stock will have ramifications for the stock and fishery. At the lower end of the *F* range leading to PGY (F_{lower}), stock biomass will be relatively high and age structure broader. At the higher end of the *F* range leading to PGY (F_{upper}), stock biomass will be lower and the age structure is likely to be more truncated by fishing, increasing the effects of recruitment variation on stock size and likely leading to more variable catches of predominantly smaller fish. Therefore, at F_{upper} (if fishing rates above F_{MSY} are permitted by the management system or occur for other reasons) there is a greater probability that spawning stock biomass *B* falls below an acceptable level. This level might be a reference point such as B_{trigger}; the level of *B* below which a pre-agreed decision rule, the harvest control rule, requires reductions in *F* [to take an example from the approach to advice by the International Council for the Exploration of the Sea (ICES, 2015; Rindorf *et al.*, 2017)]. As well as single stock considerations, changes in *F* within the *F*-PGY range will influence interactions between stocks and the wider community and ecosystem. These interactions and effects are likely to substantially modify responses predicted from single population assessments, which usually assume that natural mortality is fixed.

Here, we explore the consequences of fishing at different *F* within the range F_{lower} to F_{upper} for stocks, the fishery and fish communities. The approach is inspired by the PGY concept (Kempf *et al.*, 2016) and recent work on F_{MSY} ranges for single species in the North Sea (ICES, 2015; Rindorf *et al.*, 2017), but uniquely based on an alternative approach that simultaneously accounts for technical and multispecies interactions and uncertainty. It builds on our previous explorations of methods for assessing the long-term consequences of alternate management actions, which address uncertainty and take account of trade-offs between weight and value of yield, state of stocks and state of the environment (Thorpe *et al.*, 2016). We use an ensemble of size-based multispecies models to define *F*-PGY ranges leading to 95% of MSY for 21 interacting stocks at the Nash equilibrium, in cases where recruitment is assumed to be deterministic and stochastic, where yield from any given stock could not be improved if its *F* were changed independently. Having defined *F*-PGY ranges we assess risks to stock status and community structure that result from fishing at different points on these ranges and from fishing with different fishing fleet permutations and levels of fishing effort. These allow us to define which values of *F* within *F*-PGY ranges are considered long-term precautionary in a multispecies and multi-fleet context.

Methods

Our method involves using an ensemble of size-spectrum models to account for multispecies interactions and model parameter uncertainty. This framework is forced by a set of fleet fishing scenarios (thus accounting for mixed fisheries effects) to model the potential impacts on overall yield (in tonnage or gross economic yield by market value) of different management choices within ranges of fishing considered to be consistent with achieving pretty good yields. In this way, we can analyse the consequences of collective application of a set of PGY ranges in a mixed and multispecies setting. The requirements for this task include the following: (i) an ensemble multispecies model of the fish community, (ii) definitions of fleets and possible fishing scenarios, (iii) a definition of multispecies MSY that can provide the basis for constructing PGY ranges for all stocks in the community, and (iv) definitions of risk and reward that provide a basis for evaluating different management options within the PGY ranges. We consider each element of the method in turn in the following subsections.

A multispecies model framework for the North Sea fish community

Analyses were performed using a modified version of the length-based multispecies model initially developed by Hall *et al.* (2006) to represent the Georges Bank fish community and subsequently applied to the North Sea community (Rochet *et al.*, 2011). The model represents 21 fish species in 32 equal length classes (each c. 5 cm), spanning the full size range of species represented in the model (Supplementary Material, Table S2). Progression of individuals through length classes is represented using the deterministic von Bertalanffy growth equation (VBGE). Individuals mature when they reach a threshold size defined by a logistic model, with 50% of individuals mature at the length of maturity (Lmat) defined in Supplementary Material, Table S2. Reproduction is described with a spawner–recruit relationship, which determines the numbers of recruits entering the smallest size class from the biomass of mature individuals. Species' dynamics are linked via predation mortality (M2), which varies with predator abundance, and size and species preference. Size preference is described with a preference function based on a log-normal distribution and species preference with a diet matrix indicating who eats whom (Rochet *et al.*, 2011; Thorpe *et al.*, 2015). In each length class, individuals are also susceptible to residual natural mortality (M1) and fishing mortality (F). An ensemble approach is used, based upon a "filtered ensemble" (FE) of 188 models drawn from a population of 78 125 candidate models (the "unfiltered ensemble" or UE), with the FE being selected on the basis of the individual member's ability to persist stocks when unfished, and to simulate assessed abundances of 10 stocks between 1990 and 2010 to an acceptable degree. This ensemble approach is described in detail in Thorpe *et al.* (2015). Further details on model structure and implementation are provided in Hall *et al.* (2006) and Rochet *et al.* (2011), and additionally in Supplementary Material, with key parameters and equations summarized in Supplementary Material, Tables S1, S5 and S6.

Definitions of fleets and fishing scenarios

We described the complex of vessels fishing the North Sea in four fleet categories: beam trawlers, industrial trawlers, otter trawlers and pelagic trawlers. While ICES (2012a, b), used catch data for 88 combinations of nation, vessel size, gear type and mesh size (as a proxy for target species) to characterize the area's demersal fisheries, we preferred the simpler four fleet classification to increase the accessibility and generality of our results. These four fleets take >90% of the North Sea catch. The catch compositions for the four fleets (Supplementary Material, Table S3) were determined from data reported by Member States to the EU Scientific Technical and Economic Committee for Fisheries (STECF, 2014). These included landings as well as estimated discards, where available, by gear type. This fleet pattern (the "historic" case in Thorpe *et al.*, 2016) can be broadly characterized as follows.

Beam trawlers mainly target flatfish, particularly sole and plaice, but also take a bycatch of other species such as cod and whiting. Industrial trawlers use small mesh trawls to target forage fishes such as sandeel and Norway pout for use as fish meal and fish oil, but may take a small bycatch of whitefish (cod, haddock and whiting). Otter trawlers use demersal trawls to target bottom dwelling fishes including cod, haddock and saithe as well as the crustacean *Nephrops norvegicus*, while also taking some catches of flatfish, such as plaice. Pelagic trawlers mainly target herring and mackerel, with smaller catches of other pelagic species. The 10 000 fleet fishing scenarios examined in Thorpe *et al.* (2016) were used to derive 9216 independent fleet fishing patterns (784 duplicate patterns removed). These "unconstrained" fleet scenarios cover a wide spread of possible future fleet responses. Within this spread, a subset of 651 "constrained" scenarios was identified and subject to further analysis. This second set implies relative effort between the fleets stays within 40% of 1990–2010 patterns, and represents a spread of most likely future fleet responses, given the constraints of political and social processes. More details on the definition of fleets, their selectivities, and fishing patterns is given in Supplementary Material.

Multispecies MSY and F-PGY (pretty good yield) ranges

ICES advise on ranges of fishing mortality giving pretty good yield (PGY, defined as a yield exceeding 95% of MSY). The methods are based on single species assessments and are described in Rindorf *et al.* (2017), while examples of the resulting advice can be found in ICES (2016). Here, we construct a multispecies analogue of the ICES approach by defining a multispecies MSY using a Nash equilibrium (NE). At the NE it is not possible to increase the yield on any one stock if fishing on all the other stocks remains fixed. NE are being increasingly used as a representation of MSY (Farcas and Rossberg, 2016; Norrstrom *et al.*, 2017). They have the advantages as follows: (i) having a clear mathematical definition which reduces ambiguity about what MSY is in a multispecies context, (ii) it is possible to test whether they have been achieved by varying the fishing mortality on each stock in turn while keeping the others fixed, and (iii) if the fleet or stock is treated as a separate management entity, and each manager acted independently to maximize their return, a NE would result, so they tend to represent potentially stable solutions. In this case choosing a NE to represent multispecies MSY allows the construction of yield curves for all stocks in such a manner that achieving multispecies MSY means maximizing the yield on all the curves at the same time. The method by which we determined the NE is described in Supplementary Material.

Determining the risk and reward associated with management outcomes

We followed Thorpe *et al.* (2016), in defining a stock as being "at risk" when its biomass falls to <10% of unfished biomass. Other definitions have been suggested (Smith *et al.*, 2009), and results of a sensitivity study in which "at risk" was taken to mean biomasses <20% of unfished biomass are presented in Supplementary Material. The community-wide risk was then simply the ensemble mean risk across the 21 stocks. Hence a risk measure of 0.05 would indicate that there is a 5% chance of suffering depletion to <10% of unfished biomass when averaged over all stocks on our definition. Risks to the most vulnerable stock in the community might be significantly higher than this, dependant on the fishing scenario. Fishery yields were expressed in terms of weight and value. Values were taken as the product of weight and mean price for each species, where price was the mean first sale price for the period 2008–2012, as determined from data for UK vessels landing into ports in UK and internationally (Supplementary Material, Table S3). It was assumed that a single monetary value per stock could be applied to all landings of that stock. Management outcomes were then expressed in terms of overall risk and reward.

We considered 21 possible management targets for the *F*-PGY ranges, spanning the values from F_{lower} to F_{MSY} in 10 equally spaced steps, and then from F_{MSY} to F_{upper} in a further 10 equal steps. Outcomes were evaluated for the 9216 unconstrained scenarios at F_{lower}, F_{MSY}, and F_{upper}, and for the 651 constrained scenarios for all 21 management targets.

Community impacts of the alternate fishing scenarios were described by reporting the biomass fraction of the modelled fish community with lengths > 40 cm (dubbed the large fish indicator, LFI) and the slope of the size-spectrum (slope of relationship between log numbers in each log size class and log size, SSS). The LFI was used because it has been proposed as an appropriate indicator of the state of the North Sea fish community with a proposed target of 0.3 (Greenstreet *et al.*, 2011) and the SSS because it was previously shown to be the indicator that most closely linked fishing-induced community responses to *F* in previous analyses (Thorpe *et al.*, 2015). No target or reference level has yet been proposed for the SSS, so we just report changes in values.

The method we used for defining the *F*-PGY ranges was a multispecies analogue of the method used by ICES (2015) to define *F*-PGY ranges to support the preparation of long-term management plans for fisheries in the North and Baltic Seas. ICES determined the range F_{lower} to F_{upper} from single-species yield curves where $Y \geq 0.95 \times \text{MSY}$. ICES ensured the range was consistent with their precautionary approach by *a priori* capping of F_{upper} to the value of *F* at which the probability of *B* falling below the biomass limit reference point B_{lim} remained $< 5\%$. We also capped our *F*-PGY ranges using an analogue of the ICES approach, by capping F_{upper} to the value of *F* at which the probability of *B* falling below $0.1 \times B_0$ remained $< 5\%$ when *F*s on the other stocks were fixed at their Nash equilibrium values. We compared the capped ICES *F*-PGY ranges with our alternative estimates of capped ranges based on longer term multispecies and mixed-fishery considerations.

Results

Yield curves at the Nash equilibrium were relatively flat-topped for most species, in both the deterministic and stochastic cases, and thus a relatively wide-range in *F* produced $Y \geq 0.95 \times \text{MSY}$ (Figures 1 and 2; Supplementary Material, Figure S2). For almost all species, the deterministic Nash F_{MSY} estimate fell within the envelope of the stochastic Nash F_{MSY} estimates. The absolute values of the deterministic Nash and mean stochastic Nash are also very similar, except in the cases of two short-lived pelagic species (sprat and sandeel) when the deterministic Nash F_{MSY} was >0.1 higher (Figure 1). The results that follow are based on the stochastic analyses, but results obtained with the deterministic approach were qualitatively comparable, even though absolute risks of collapse were lower. Comparisons between approaches demonstrated that differences in parameterizations of plausible models in the filtered ensemble (influencing the strength of mixed fisheries and multispecies interactions) made a greater contribution to uncertainty about future states than stochasticity in recruitment.

Risks of stock collapse increased across the *F*-PGY range from F_{lower} to F_{upper}, although fishing all stocks at F_{upper} could lead to slightly greater total weight or value of yield from the whole fishery for most fleet configurations than when fishing at F_{MSY} (Figure 3). Fishing at F_{MSY} or F_{lower} resulted in high fishery wide yield with low risk for some fleet permutations. For demersal stocks alone (Figure 3), risks are generally significantly lower at a given point on the *F*-PGY range, showing that a disproportionate fraction of overall risk comes from the response of the pelagic stocks. When fleet permutations were constrained, the relationships between risk and overall weight or value were less variable than in the unconstrained case (Figure 3). Unsurprisingly, risks of stock collapse are higher for all stocks and for demersal stocks when a $0.2 \times B_0$ risk threshold is used, but the pattern of response is similar to that for $0.1 \times B_0$. With a $0.2 \times B_0$ risk threshold all fleet permutations led to a risk of collapse >0.05 when fishing at F_{upper} (Supplementary Material, Figure S3). With constrained fleets, fishing mortality rates on each stock are predominantly linked to risks of $<10\%$ that *B* will fall below $0.1 \times B_0$ for any stock when fishing at F_{lower}. Fishing mortality ranges are narrower and risks lower for demersal stocks (Figure 4). At F_{MSY} and F_{upper}, *F* ranges and the proportion of permutations where risks that *B* will fall below $0.1 \times B_0$ are $>10\%$ both increase (Figure 4). The dominant choke species with unconstrained and constrained fleets were cod and cuckoo ray. Our results can also be expressed to show how the risk of collapse to below $0.1 \times B_0$ or $0.2 \times B_0$ varies across the *F*-PGY ranges (Table 1). The fraction of fleet scenarios giving at least 5% risk of collapse to $<0.1 \times B_0$ is 0.55 when fishing all stocks at F_{lower} (assuming constrained fleets), but rises to 0.98 for $0.2 \times B_0$. At F_{MSY} the fraction of fleet scenarios with 5% risk of collapse to $<0.1 \times B_0$ rises to 0.92. If choices of *F* are deemed multispecies precautionary only when the proportion of stocks at risk of collapse is <0.05, then fishing at F_{lower} is not precautionary for around half the fleet permutations when considering both pelagic and demersal stocks (Figure 3). Fishing at F_{lower} or F_{MSY} is, in general, multispecies precautionary for demersal stocks whether fleets are constrained or not. Qualitatively

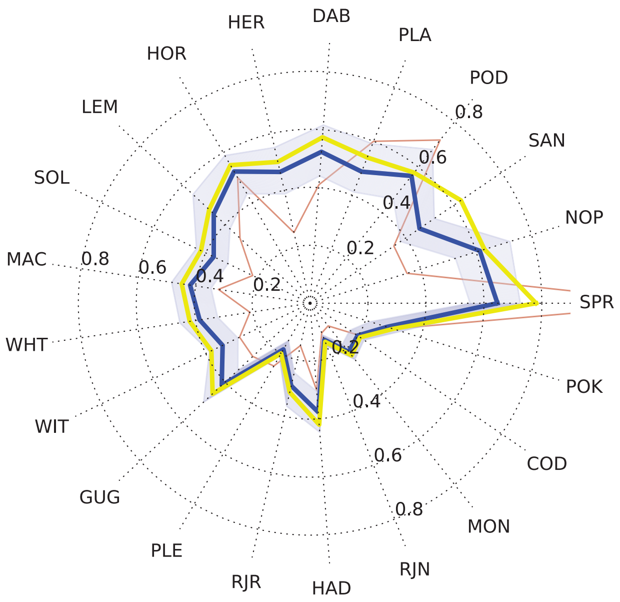

Figure 1. Radar plot of F_{MSY} estimates for the 21-stock stochastic Nash equilibrium (blue line) with 95% confidence interval, compared with the deterministic Nash equilibrium (yellow), and estimates from single species assessments (brown). SPR, sprat; NOP, Norway pout; SAN, sandeel; POD, poor cod; PLA, long rough dab; DAB, dab; HER, herring; HOR, horse mackerel; LEM, lemon sole; MAC, mackerel; WHT, whiting; WIT, witch; GUG, grey gurnard; PLE, plaice; RJR, starry ray; HAD, haddock; RJN, cuckoo ray; MON, monkfish; COD, cod; POK, saithe.

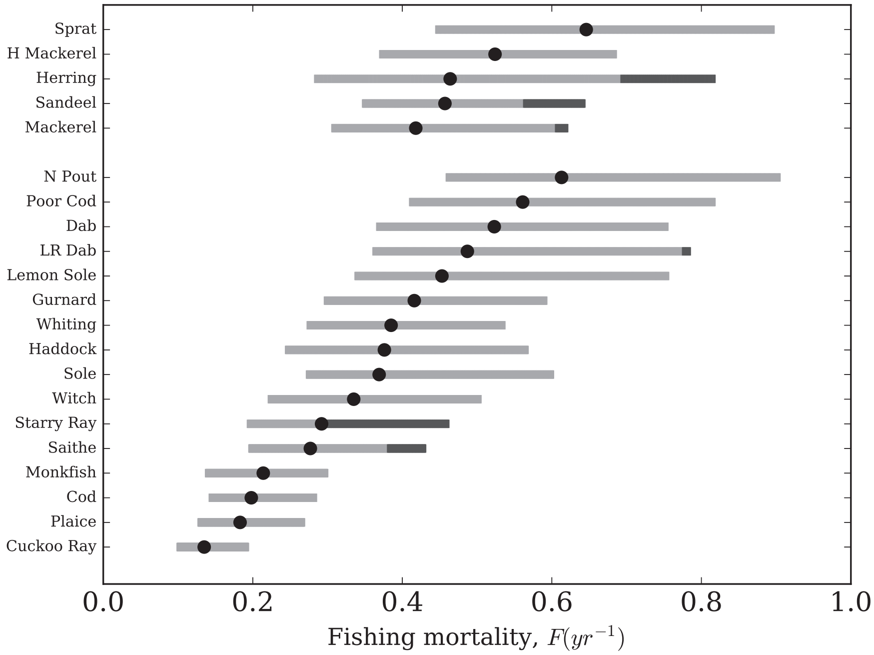

Figure 2. *F*-PGY ranges based on the 21-stock Nash equilibrium. Grey bars span the *F*-PGY ranges, with the black circle denoting the estimate of F_{MSY}. Pelagic stocks are grouped at the top. Dark grey shows where ranges have been capped in order to keep the risk of stock depletion $<5\%$.

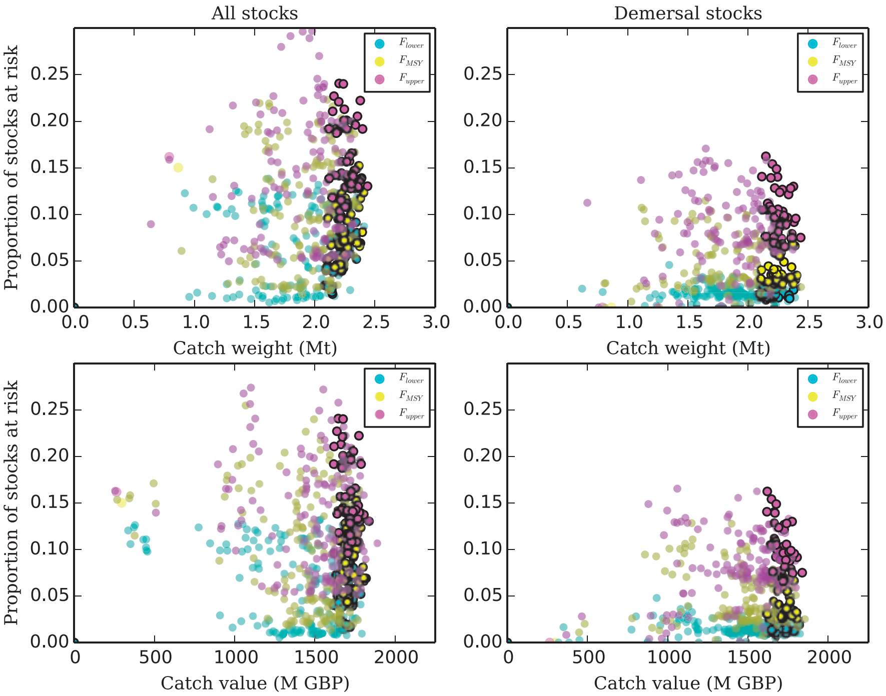

Figure 3. Relationship between the proportion of stocks "at risk" ($B < 0.1 \times B_0$) and yield by weight or value. Symbols indicate ensemble mean estimates. Outcomes are shown for fishing at F_{lower} (cyan), F_{MSY} (yellow) and F_{upper} (magenta) with all fleet permutations (unconstrained, no border on symbols) and with constrained fleet permutations (bordered symbols). Uncertainty resulting from alternate fleet configurations is indicated by the spread of points. Risk is presented as proportion of all stocks in the left-hand column, whereas the right-hand plots show the risk to demersal stocks only, with risks against pelagic stocks being ignored.

comparable relationships between F and risk are seen when applying the $0.2 \times B_0$ threshold for collapse, but the absolute probability of fishing not being precautionary is much higher (Supplementary Material, Figures S3 and S4), particularly for demersal stocks. When we performed sensitivity analyses in which non-assessed species were not treated as potential choke species, and in which their estimated mortality rates were halved, the general pattern of increasing risk for marginal increases in overall catch weight or value across the F-PGY range was upheld. However, for the constrained fleets, higher rates of F within the F-PGY range were slightly less risky (Supplementary Material, Figure S5).

Model results suggest that values of the LFI above a proposed threshold for the North Sea (0.3; Greenstreet *et al.*, 2011) could be achieved even when the fleet permutation and location on the F-PGY ranges led to a relatively high risk of stock collapse (Figure 5). For the constrained set of fleet permutations, the ensemble mean LFI is >0.3 at F_{lower}, whereas for F_{upper} it is below this (Figure 5), suggesting that fishing closer to F_{lower} will increase the chance that the LFI remains above the proposed threshold. This pattern also holds good if a stricter definition of stock collapse of $B > 0.2\ B_0$ is used (Supplementary Material, Figure S6). The response of the SSS to fishing at different points on the F-PGY range is similar to that of the LFI. The SSS tends to steepen with higher levels of fishing, but it is possible for a shallower SSS to co-exist with a high risk of stock collapse with some fleet scenarios (Figure 5).

For the subset of constrained fleets, we examined the impacts on risk and reward of increasing F in 10 equal steps from F_{lower} to F_{MSY}, and in a further 10 from F_{MSY} to F_{upper}. Results for the ensemble mean and individual fleet scenarios illustrate increasing risk and reward when moving from F_{lower} to F_{upper} (Figure 6). However, risk increases much more rapidly than reward, such that moving from F_{MSY} to F_{upper} doubles risk with no effective change in total catch value. For the ensemble mean, the risk of stock collapse just exceeds 0.05 when fishing at F_{lower}, while at F_{MSY} it rises to >0.1 (Figure 6).

It was possible to compare capped ICES F-PGY ranges from single-species assessments with our estimates of capped ranges, based on longer term multispecies and mixed-fishery considerations, for five stocks in our modelled community. Ranges based on the two approaches were almost identical for haddock, plaice and saithe, but the long-term multispecies and mixed-fishery based ranges were higher and wider for sole and lower and narrower for cod (Table 2).

Discussion

In this mixed and multispecies fishery, our simulations suggest that reward (total weight and value of yield from all fished populations) increased marginally when fishing all populations at the upper end of F-PGY ranges. However, risks to populations and communities also increased markedly towards the upper end of the F-PGY ranges, such that the gross value of yield per unit risk decreases by a factor of four. When F was reduced to rates at the lower end of F-PGY ranges the risks of population collapse were substantially reduced but there were small impacts on fishery-wide yield and value. Our simulations suggest that the greatest collective long-term benefits from this mixed and multispecies fishery will be achieved when F is held close to, or below, F_{MSY} for all species. This result was shown to be robust for many

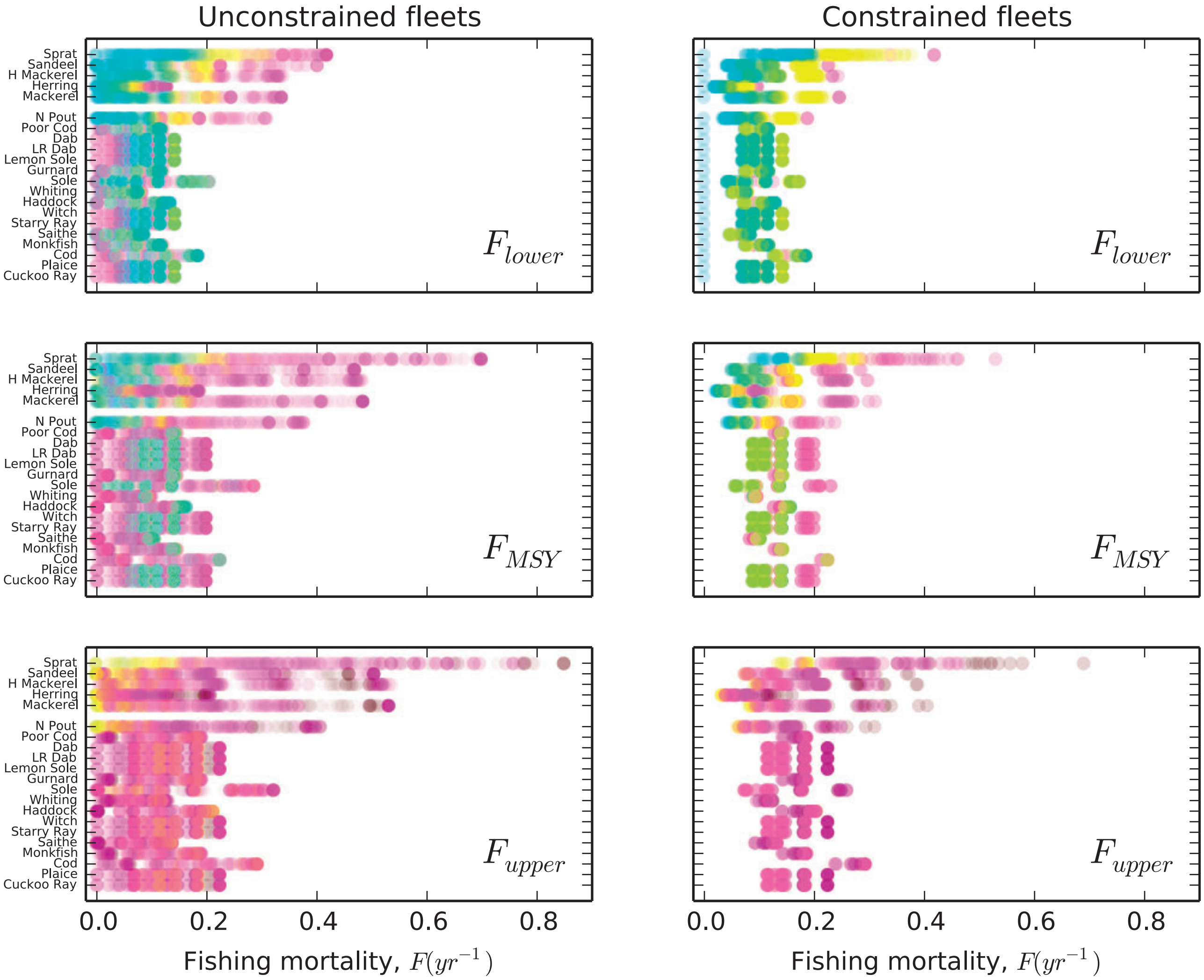

Figure 4. Fishing mortality rates by stock when fishing at F_{lower}, F_{MSY} and F_{upper} (top to bottom) with unconstrained fleet permutations (left column of panels) and constrained fleet permutations (right column). Symbols indicate ensemble mean estimates. Variations in F on individual stocks which result from the alternate fleet permutations are indicated by the spread of symbols. Cyan symbols indicate <5% risk of stock collapse across the community with $B < 0.1 \times B_0$, yellow symbols indicate 5–10% average cross-community risk of $B < 0.1 \times B_0$, magenta indicates 10–20% average cross community risk of $B < 0.1 \times B_0$, and dark red over 20% average cross community risk of $B < 0.1 \times B_0$.

plausible fleet permutations, but even our broad exploratory approach does not account for the potential emergence of new fleets, changes in targeting by existing fleets and the loss of existing fleets that might occur in the medium to long-term.

For pelagic stocks with unconstrained fleets the risk of collapse is frequently >0.05 when fishing at F_{lower} or F_{MSY}, although risks are reduced when fleet changes are constrained. Relatively modest F can lead to relatively high risk of population collapse for pelagic stocks and Norway pout. This is because reduced F on demersal predators, such as cod and saithe, will cause their biomass to increase and, in turn, increase the rate of predation on small pelagics and Norway pout. This higher rate of predation mortality increases the risk of population collapse when fishing pelagic stocks and Norway pout at a given F. Thus, if we continue to reduce fishing pressure on North Sea cod and stock size grows, F_{MSY} for any stock where cod predation accounts for a significant proportion of natural mortality is expected to fall.

The incorporation of stochastic recruitment in the simulations led to higher estimates of risk than those obtained from an assumption of deterministic recruitment. However, model parameter uncertainty was more important than recruitment uncertainty in determining the overall levels of risk. ICES single-species assessments already account for stochastic recruitment, so the additional risk we report with a multispecies mixed fishery approach is predominantly driven by two processes. First, multi-species interactions may impose additional natural mortality on some stocks following changes in fishery targeting, so risk of population collapse is increased at a given F (e.g. pelagics and Norway pout as above). Second, the variations among models in the filtered ensemble add risk because they reflect uncertainty about parameter values.

Our approach is intended to inform a strategic view of the consequences of alternate management actions in mixed and multispecies fisheries. A comparison with ICES (2015) F-PGY ranges for five demersal stocks also included in our analysis shows similar results for haddock, plaice and saithe, suggesting that for these stocks efforts to meet objectives for single species management appear to align with reducing risk of population collapse in a mixed and multispecies fishery and with meeting targets for the LFI. The higher estimates for sole suggests that in this case, mixed fisheries and multispecies effects may support a higher level of fishing on the stock. Estimates of F_{lower} for cod are similar, but the mid and upper parts of the *F*-PGY ranges are significantly lower in this case, suggesting that fishing in the upper part of the ranges may not be consistent with achieving PGY for cod. However, from the broader perspective of maximizing overall yield, it may be beneficial to fish cod at higher *F* (foregoing some yield on cod) in order to increase the yield on other stocks which are impacted by cod predation. Quantifying the extent of this effect is beyond the scope of the current study, but could be addressed in the future within our modelling framework. The contrasting results for cod and sole illustrate the importance of including multispecies and mixed fisheries considerations in the determination of reference points.

Estimated fishery-wide yields by weight were ~25% lower than yields estimated with the same ensemble of multispecies models by Thorpe *et al.* (2015). Total yield is lower in the present analysis because of the impact of stochastic recruitment and because we required that no stock should be fished at $F > F_{\text{target}}$. In this mixed-fishery, this led to “choking”, where one species limited the catch of others in the fishery due to an imbalance in exploitation rates across species (Ulrich *et al.*, 2011). The previous study, conversely, examined the case where we allowed independent control of *F* for each species. Ongoing moves towards achieving greater independent control of *F* are expected to increase total volume and value of yield from these mixed multispecies fisheries, without increasing risks of stock collapse.

Table 1. Table summarizing risk of fishing at different locations on the *F*-PGY range for unconstrained fleets and all stocks; constrained fleets and all stocks; unconstrained fleets and demersal stocks; and constrained fleets and demersal stocks.

Scenario	***F* target**	**Risk (B<0.1 B_0)**	**Risk (B<0.2 B_0)**
• Unconstrained fleets	F_{lower}	52	100
All stocks	F_{MSY}	72	100
	F_{upper}	99	100
• Constrained fleets	F_{lower}	55	98
All stocks	F_{MSY}	92	100
	F_{upper}	100	100
• Unconstrained fleets	F_{lower}	0	89
Demersal stocks	F_{MSY}	35	95
	F_{upper}	86	96
• Constrained fleets	F_{lower}	0	98
Demersal stocks	F_{MSY}	25	100
	F_{upper}	100	100

Values in each cell indicate the proportion of fleet permutations where the ensemble mean community average risk of $B < 0.1\ B_0$ or $B < 0.2\ B_0$ is $> 5\%$. If we assume all fleet scenarios are equally likely then white shading indicates a low (<5%) probability that *B* does not fall below the 0.1 B_0 or 0.2 B_0 threshold, light grey 5–75% probability, dark grey >75–99% probability and black 100%.

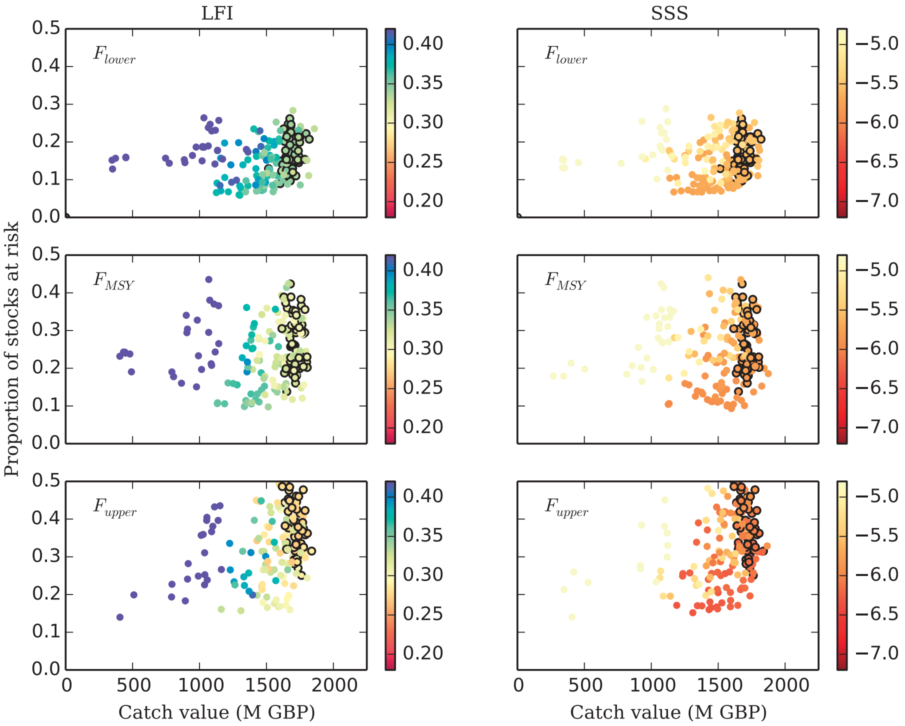

Figure 5. Relationships between the proportion of stocks “at risk” ($B < 0.1 \times B_0$), catch value and values of the community indicators dubbed the “large fish indicator” (LFI, left panels and associated scales) and “slope of the size spectrum” (SSS, right panels and associated scales). Symbols indicate ensemble median estimates. Outcomes are shown for fishing at F_{lower}, F_{MSY} and F_{upper} with all fleet permutations (unconstrained, no border on symbols) and with constrained fleet permutations (bordered symbols). Uncertainty resulting from alternate fleet configurations is indicated by the spread of points.

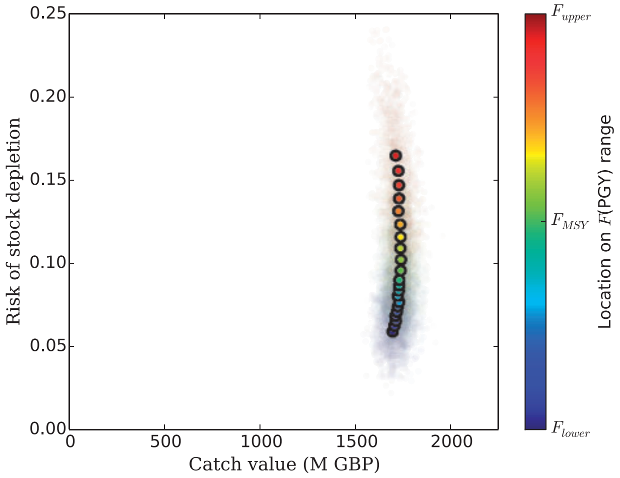

Figure 6. Relationships between the proportion of stocks "at risk" ($B < 0.1 \times B_0$) and catch value. Outcomes are shown for fishing at successive points in the range from F_{lower} to F_{upper}, where blue indicates lower regions of the range, red upper regions, and pale green denotes fishing at F_{MSY}. Ensemble mean outcomes are shown by the coloured circles. Uncertainty resulting from alternate fleet configurations where fleet efforts are constrained to lie within a factor of 1.8 of each other (the "constrained fleets") is indicated by the spread of points, coloured by fishing level.

Table 2. F_{MSY} ranges based on the Nash equilibrium and accounting for long-term multispecies and mixed-fishery considerations (Nash) and as estimated by ICES (2015).

Stock	F_{lower}	F_{MSY}	F_{upper} (capped)
Plaice			
ICES	0.13	0.19	0.27
Nash	0.13	0.18	0.25
Sole			
ICES	0.11	0.20	0.37
Nash	0.33	0.37	0.48
Haddock			
ICES	0.25	0.37	0.52
Nash	0.29	0.37	0.45
Cod			
ICES	0.22	0.33	0.49
Nash	0.18	0.20	0.25
Saithe			
ICES	0.20	0.32	0.43
Nash	0.24	0.28	0.38
Modelled risk			
Nash	6%	9%	17%
Yield per stock at risk			
Nash	£1350M	£950M	£490M

In both analyses, the value of F_{upper} based solely on PGY considerations was capped to reduce risk of stock collapse. Modelled risk is the probability of collapse of any stock to 0.1 B_0 when fishing at F_{lower}, F_{MSY} or F_{upper} and yield per stock at risk is the mean value of yield expressed as a proportion of the probability of collapse at each fishing rate.

Cod and cuckoo ray were particularly influential as choke stocks. Cod has a relatively low F-PGY range and the otter trawl fleet is relatively more efficient at catching cod while cuckoo ray has a lower F-PGY range than any of the main commercial stocks. If mortality rates of cod and cuckoo ray could be further decoupled from those for other demersal species, then overall yields could be increased without changing risk. Such decoupling has been a focus of efforts to manage mixed fisheries in Europe (Kraak *et al.*, 2013) and elsewhere (Dunn *et al.*, 2011) in recent years, with changes in fishing gear and spatio-temporal management measures likely to play an increasingly important role in mixed fisheries management as managers seek to reconcile trade-offs.

There are several caveats associated with the modelling approach and its application to these fisheries. Caveats associated with the multispecies model have been described elsewhere (Hall *et al.*, 2006; Rochet *et al.*, 2011; Thorpe *et al.*, 2015, 2016). Here, we emphasize that the treatment of body growth will influence our results because we assume that predators always get enough food. This will influence the relationship between predator and prey species in two ways. First, the existence of a reservoir of "other food" buffers prey against predation by predators and tends to reduce the strength of predator–prey interactions. Second, the biomass of predators can increase further than it would if food was a limiting factor, and this tends to increase the strength of the interaction. In the absence of an explicit representation of food-dependent body growth, it is not clear which process would dominate. Better understanding of the effects of food limitation on stock dynamics could be gained by running comparisons with alternate models which seek to represent food-dependent growth (Blanchard *et al.*, 2014).

The model did not include some of the most sensitive fish species in the North Sea. The cuckoo ray, a medium sized species of ray was the main non-target choke species in our model, but it is not the most sensitive ray species present in the North Sea (Walker and Hislop, 1998). If more sensitive species were included then these would likely choke the fishery at lower rates of F than the cuckoo ray. However, there are insufficient catch and F estimates for more sensitive non-assessed species to represent their role in the fisheries reliably.

We also assumed that the F affecting non-assessed species could be as high as the F affecting similar assessed species (by length). There are no comprehensive data to substantiate the validity of this assumption, but this upper bound on F for non-assessed species is likely to be reasonable in most circumstances where fishers will not be prioritizing the capture of non-assessed and predominantly non-target species (Pope *et al.*, 2000). Other descriptions of the effects of North Sea fisheries on the status of non-assessed species, also imply they are affected by F that approaches, but is not above, F for assessed species (Walker and Hislop, 1998; Piet *et al.*, 2009; ICES, 2012c). When we took a conservative approach, and assumed that the upper bound of F for non-assessed species was 50% of F of assessed species by length, results were qualitatively similar but absolute risk associated with any given F was slightly reduced.

The method used to generate the posterior distribution is a form of rejection algorithm (Tavaré *et al.*, 1997), the simplest form of Approximate Bayesian Computing (ABC, Csillèry *et al.*, 2010). Parameters of each size-based model in the unfiltered ensemble are sampled from parameter distributions and the simulated data generated by each model run are compared with "observed" data to determine whether each model is accepted to the filtered ensemble. Clearly, the quantification of uncertainty is conditional on the modelling framework used and the tolerance window used for deciding whether to accept or reject a parameter set. We allowed significant leniency, because the "observed" data were model output from single-species stock assessments, but we have previously demonstrated that our approach is relatively robust to changes in leniency and to different discretizations of parameter space (Thorpe *et al.*, 2015). The value of ABC type methods has been questioned, especially on grounds that posterior probabilities are too far away from true probabilities to provide a valid indicator of risk (e.g. owing to weaknesses in model frameworks or adequacy of the statistical data used for assessment). Ultimately, probabilities and hence risk must be conditional on the integrated effect of all their constituent assumptions, but we have found our approach robust in relation to tolerance definition, choice of prior parameter ranges, number of dimensions and implementation error linked to complexity of evaluation (Thorpe *et al.*, 2015; see Supplementary Material).

Management strategy evaluation (MSE, Butterworth and Punt, 1999; Punt *et al.*, 2014) is often used to test the robustness of each part of a management cycle to various sources of uncertainty (recruitment, measurement error and policy implementation error). We did not conduct this analysis as a MSE because our emphasis was on exploring the nature of the multispecies MSY decision space expressed as risk vs. reward, and its implications for potential trade-offs, rather than on the performance of multispecies harvest control rules; although the model framework used in this study could readily be adapted to provide a set of operating models within MSE.

We conclude that our application of an ensemble of size-based multispecies models to define *F*-PGY ranges in a mixed multispecies fishery provides insights into the consequences of trying to obtain PGY that can likely be generalized to other mixed fisheries that catch a range of stocks with differing productivities. While the total weight and value of yield from all fished stocks may increase marginally when fishing all stocks at the upper end of *F*-PGY ranges this is linked to a disproportionate increase in risk of stock collapse. Consequently, reducing *F* to rates at the lower end of *F*-PGY ranges substantially reduces risks of stock collapse and increases community resilience, but with small impacts on combined yield or value from the whole fishery. The advantage of *F* ranges for managers is that they provide some flexibility to address social and economic trade-offs: to manage transition costs when moving to F_{MSY} from higher rates of *F* and to deal with imbalances in quota availability in mixed fisheries. However, our results suggest that the greatest collective long-term benefits from mixed multispecies fisheries will be achieved when *F*-PGY is close to or below F_{MSY} as defined at the Nash equilibrium.

Supplementary data

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

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