ICES Journal of
Marine Science

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

ICES Journal of Marine Science (2017), 74(2), 552–565. doi:10.1093/icesjms/fsw119

Contribution to the Symposium: '*Targets and Limits for Long Term Fisheries Management*'

Original Article

Combining stock, multispecies, and ecosystem level fishery objectives within an operational management procedure: simulations to start the conversation

Sarah K. Gaichas[1]*, Michael Fogarty[1], Gavin Fay[2], Robert Gamble[1], Sean Lucey[1], and Laurel Smith[1]

[1]*NOAA NMFS Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543, USA*
[2]*School for Marine Science and Technology, University of Massachusetts Dartmouth, 200 Mill Road, Fairhaven, MA 02719, USA*

Corresponding author: tel: +1 508 495 2016; fax +1 508 495 2258; e-mail: sarah.gaichas@noaa.gov

Gaichas, S. K., Fogarty, M., Fay, G., Gamble, R., Lucey, S., and Smith, L. Combining stock, multispecies, and ecosystem level fishery objectives within an operational management procedure: simulations to start the conversation. – ICES Journal of Marine Science, 74: 552–565.

Received 1 February 2016; revised 7 June 2016; accepted 9 June 2016; advance access publication 18 July 2016.

We explored alternative status determination criteria and reference points that could simplify fisheries management using a simulated multispecies/ecosystem-based operational management procedure. There are four components to the procedure: (i) limit total removals from the ecosystem; (ii) allocate the total removals limit among aggregate species groups; (iii) maintain individual species above minimum stock size thresholds; and (iv) optimize the species mix (within aggregates) based on bio-economic portfolio analysis. In this procedure, "overfishing" criteria are applied only to aggregates of species at the ecosystem and group level, but "overfished" criteria apply at the species/stock level. Previous work using multispecies production models identified conditions where conservation and yield objectives could be balanced: aggregations of species with similar life histories, species interactions, and responses to environmental forcing supported the highest yields while minimizing risks that individual stocks dropped below biomass thresholds. Here, we use a more complex length structured multispecies, multifleet simulation model to explore management procedure steps (i)–(iii). Different species aggregation rules were applied (single species, functional groups, and full system), and yield curves were constructed for each aggregation level by sequentially increasing effort in each of the fleets (alone and simultaneously), while recruitment for each species varied stochastically around a function based on spawning stock biomass. The performance of individual species and each aggregate type was then compared with respect to yield, biomass, and economic revenue objectives under changing environmental conditions. Our results evaluate the trade-offs between these objectives for the 10 species in the simulated system. Overall we found that there are aggregate catch limits that can both maximize yield and revenue while conserving biomass. However, community composition and revenue trade-off over a range of fishing effort. We consider this a starting point for further development with scientists, managers, fishermen, and other stakeholders in the region.

Keywords: Georges Bank, management strategy evaluation, multispecies fisheries, multifleet fisheries, simulation modelling.

Introduction

In many regions worldwide, there is general agreement that fishery resources should be managed according to the tenets of Ecosystem Based Fishery Management (EBFM; e.g. Pikitch *et al.*, 2004). The question now is how to operationalize EBFM. The general goals of EBFM have been well described (e.g. Murawski, 2000; Link, 2010), and include maintaining ecosystem and stock productivity, maintaining diversity as "insurance" against changing conditions, and considering humans as part of the ecosystem. Under the US law, there are already clear objectives to prevent overfishing (exceeding annual catch limits), avoid overfished status (reducing stocks below biomass thresholds), and rebuild overfished stocks (Methot *et al.*, 2014). Applied at species level, fishery management plans (FMPs) can be for one or many species (National Marine Fisheries Service, 2015). FMPs generally apply to specific stocks or resources, while regulations managing fisheries to achieve these objectives across multiple FMPs are implemented simultaneously within an ecosystem without accounting for potential conflicts or trade-offs. Fishermen therefore negotiate a complex web of regulations under current management systems (making food webs look simple), and yet formal consideration of climate, habitat, species, fleet, market, and human community interactions is difficult within the current FMP structure. Considering these linkages is vital to developing functional management strategies (Degnbol and McCay, 2007). While often considered separately from biological objectives, other objectives for human well-being are nevertheless considered in management: maintain/improve economic returns, increase predictability or stability of returns, and reduce complexity, or at least do not make management systems more complex than they already are. A practical approach to EBFM would make trade-offs between these multiple objectives transparent while remaining relatively easy to implement and operationalize.

Operational management procedures (OMPs) are distinguished from most current US fishery management systems in fully specifying a complete package of input data, assessment tools, and management measures for a particular resource and its associated uncertainties. Simulation testing to evaluate the full package including alternative management strategies is termed management strategy evaluation (MSE) and is central to developing an OMP (Smith, 1994; Punt *et al.*, 2014b). OMPs are designed to balance transparency, simplicity, and stability of results with meeting stated management objectives. While complex quantitative assessments are important for estimating reference points and evaluating stock status on a periodic basis, relatively simple OMPs can perform comparably to or better than complex quantitative assessments for providing annual catch advice (Geromont and Butterworth, 2015). During development, OMPs require substantial investment from all stakeholders in fishery management to ensure that appropriate management objectives and performance measures are defined and that contingency plans are developed for likely future scenarios (Plagányi *et al.*, 2007; Rademeyer *et al.*, 2007). However, it may be useful to have worked simulation examples to provide illustrations of different management strategies during initial development of an OMP, in particular when the management measures have not been applied together previously. Providing such a preliminary example as a "thought experiment" is our objective here.

There are four components to the proposed ecosystem-based management strategy we examine (Fogarty, 2013): (i) limit total removals from the ecosystem (Brown *et al.*, 1976); (ii) allocate the total removals limit among aggregate species groups; (iii) maintain individual species above minimum stock size thresholds (as is current practice); and (iv) optimize the species mix (within aggregates) based on bio-economic portfolio analysis (Edwards *et al.*, 2004; Sanchirico *et al.*, 2008). Here we emphasize interactions and trade-offs among the first three components, with the fourth to be integrated later based upon Jin *et al.* (2016). Input data required include the total catch from the ecosystem and each aggregate species group, current and reference biomass levels for each species, and information on economic revenue. In this OMP, "overfishing" criteria are applied only to aggregates of species at the ecosystem and group level, but "overfished" criteria apply at the species/stock level. This OMP is intended to simplify management by requiring accounting against fewer catch limits, and using an integrated assessment of interacting species to determine stock status.

Previous work using multispecies production models identified conditions where conservation and yield objectives could be balanced in a fished multispecies system: aggregations of species with similar life histories, species interactions, and responses to environmental forcing supported the highest yields while minimizing risks that individual stocks dropped below biomass thresholds (Gaichas *et al.*, 2012). A shortcoming of this work was that multispecies yield curves were evaluated assuming that fishing mortality rates were increased simultaneously and equally for all species, which does not happen in reality. Instead, multiple fishing fleets catch different proportions and size classes of the marine creatures they encounter depending upon their fishing gear, fishing methods, locations, experience, and economic objectives. Here, we use a more complex length structured multispecies, multifleet simulation model to explore whether the management strategy proposed can balance catch quantity and revenue with species conservation.

Methods

Simulation model

The operating model (Hydra; Supplementary data) is implemented in ADMB (Fournier *et al.*, 2012) and simulates 10 species with length-structured population dynamics and predation (structured as in Hall *et al.*, 2006; Rochet *et al.*, 2011), and fishery selectivity with fishing mortality coming from three effort-driven multispecies fleets. Multiple forms for growth and recruitment are implemented in the operating model so that each species may have different combinations within the model structure (e.g. von Bertalanffy growth with Ricker recruitment, exponential growth with Beverton–Holt recruitment) and environmental covariates for each function can also be included. For simulations presented here, only temperature-dependent consumption was included and forced for all species by the same time series of annual average bottom temperature on Georges Bank (NEFSC, 2012, 2015). There is no feedback between prey consumption and predator growth in Hydra, similar to most multispecies population dynamic models; predation is included to account only for mortality on prey (e.g. Magnússon, 1995).

The 10 species included in the model are key commercial species in the Georges Bank fish community, historically a heavily exploited ecosystem (Fogarty and Murawski, 1998). They can be organized into functional groups in many ways (see, e.g. Gaichas *et al.*, 2012), but here we categorize by a combination of taxonomy and foraging mode to include two piscivorous Elasmobranchs (spiny dogfish and winter skate), two pelagic Planktivores (Atlantic herring and Atlantic mackerel), three demersal Piscivores (Atlantic cod, silver hake, and monkfish), and three demersal invertebrate feeders or Benthivores (haddock, yellowtail flounder, winter flounder). Scientific names and a summary of aggregate group membership are listed in Table 1. Parameterizations for growth, recruitment, and fishery size selection were based on Georges Bank survey and fishery data to the extent possible, although fishery size selectivity, species catchability, and fishing effort should be considered illustrative for the analysis rather than representative of actual fishing fleets operating at present. Similarly, simulated population levels and yields

Table 1. Simulated species common names, scientific names, and aggregate group membership. Individual species are listed in the same order in all figures and tables.

Common name	Species	Aggregate group name
Spiny dogfish	*Squalus acanthias*	Elasmobranchs
Winter skate	*Leucoraja ocellata*	Elasmobranchs
Atlantic herring	*Clupea harengus*	Planktivores
Atlantic cod	*Gadus morhua*	Piscivores
Haddock	*Melanogrammus aeglefinus*	Benthivores
Yellowtail flounder	*Limanda ferruginea*	Benthivores
Winter flounder	*Pseudopleuronectes americanus*	Benthivores
Atlantic mackerel	*Scomber scombrus*	Planktivores
Silver hake	*Merluccius bilinearis*	Piscivores
Monkfish	*Lophius americanus*	Piscivores

for the included species should be considered illustrative rather than representative of current status and dynamics because the simulation model has not been formally fit to biomass or catch data from this system. More details on model equations and parameterization are included in Supplementary data, Tables S1–S4, and key functions are illustrated for each species and fishing fleet in Supplementary data, Figures S1–S4.

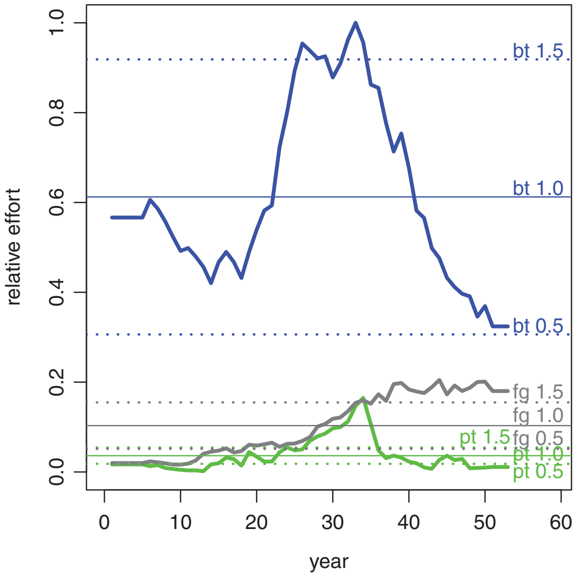

Figure 1. Simulated effort levels for each fishing fleet compared with regional observed effort [bottom trawl (bt) = blue at top, fixed gear (fg) = grey intermediate, pelagic trawl (pt) = green at bottom)]. Effort level 1.0 (solid horizontal line) is the average of the regional observed effort for each fleet; effort levels 0.5 and 1.5 (dotted horizontal lines) illustrate proportions of average effort for each fleet, with 1.5 as the maximum effort used in the simulation. Note that effort levels fg 0.5 and pt 1.5 overlap on the plot.

Simulation design

Yield curves were constructed for each species, aggregate group, and the entire 10 species system. They were created by simulating a range of constant fishing effort in 10% increments from no fishing to 150% of the historical average effort (or proportions of average effort ranging from 0.0 to 1.5). This was done for all fishing fleets together, as well as each fleet separately, over a 50-year period (Figure 1). Bottom trawl effort, scaled from fishing days to standardized units, dominated overall fishing effort in this simulation. To represent stochastic variability in recruitment dynamics, an ensemble of 500 model runs with random deviations drawn from the recruitment curve for each species was subject to each of the 16 levels of simulated fishing effort.

The purpose of this “thought experiment” is to evaluate potential trade-offs between objectives to determine whether the management procedure is worth examining further, rather than to find the optimal mix of gears or effort levels to achieve certain objectives. (The latter analysis would need to be done in consultation with managers and stakeholders where objectives are clearly specified within a full MSE process.) Using the individual fleet results above, we briefly evaluate two different permutations of fleet effort levels as an example of further analyses that could be done to investigate whether performance can be improved over the all-fleets-combined performance.

Stock assessment

Perfect knowledge of species biomass and catch by fleet at each time-step was assumed for this analysis. Therefore, the only uncertainty considered here was stochastic recruitment variability; simulation results were used directly to calculate performance metrics, without adding error because of sampling, incomplete data collection, or imprecise stock assessment.

Performance metrics

To represent non-stationary environmental processes and changing species interactions because of the different mix of life histories represented in the model, we evaluated performance metrics at two snapshots (time-steps 20 and 50) during the model run. This model was not run to equilibrium under fixed conditions; rather, as an operating model it includes key non-stationary processes to represent the more complex “real world”. Water temperatures on the US Northeast continental shelf are increasing more rapidly than much of the world ocean (Hobday and Pecl, 2013; Hare *et al.*, 2016). Bottom temperature on Georges Bank has warmed by ∼0.5 °C since the early 1970s (NEFSC, 2012, 2015), so this was included in the model, and has the potential to change predation dynamics (Supplementary data, Equation S14). The relatively rapid change in temperatures here suggests that biological processes may not have the opportunity to equilibrate before further change happens. This admittedly presents a conceptual difficulty with stock reference points, which are generally derived in an equilibrium context (but applied in a real-world, non-stationary context). However, we considered snapshots of performance under contrasting conditions preferable to assuming a non-existent equilibrium.

To evaluate stock conservation status, we used the ratio of current biomass relative to unfished biomass. Unfished biomass (B0) for this simulation is defined as the biomass of each species where no fishing occurs on any species in the ecosystem (while predator prey dynamics continue in all simulations). B0 is defined here as the unfished biomass at a particular time-step for a particular ensemble member; this is derived from the baseline run with 0 fishing effort. Although the model was not run to equilibrium as explained above, we did not evaluate B0 for time-steps prior to year 20 to avoid the transient period of population release from fishing observed in the baseline model run for most species. The ratio of current biomass to B0 from each fishing effort increment above 0 was also calculated for each ensemble member. A minimum stock biomass threshold of 20% of unfished biomass (B0) was selected for all species as a starting point for comparison, although this common limit reference point is not universally applicable across life history types (Mace, 1994; Gabriel and Mace, 1999). We note that the typical biomass limit reference point used in the US is ½ B_{MSY} (Methot *et al.*, 2014), which would not necessarily equal 20% of B0 for a given stock. However, comparisons between reference points based on B0 and B_{MSY} suggest that B_{MSY} is generally approximated between 35 and 40% B0 (Punt *et al.*, 2014c); therefore, our selection of 20% B0 as a limit reference point may generally approximate the US overfishing limits based on ½ B_{MSY}. We considered a species to be above the biomass threshold if the median current biomass/B0 ratio of the 500 member ensemble remained above the threshold, but we show the full range of results.

To evaluate fishery performance, we used both yield in tons from each simulation and value in dollars. Economic revenue was defined very simply here by multiplying 2012 ex-vessel price for each species (National Marine Fisheries Service, 2014; Supplementary data, Table S4) by the simulated landings for that species for each ensemble member. We used the median result of the 500 member ensemble to compare yield and revenue across effort levels, but show the full range of results characterizing uncertainty for a subset of fleet/effort combinations.

Using these performance metrics, we can address the following specific questions regarding the general performance of the proposed management strategy:

- Is there a clear maximum yield to specify a total catch cap for the system?
- Are there clear yield maxima for aggregate species groups to guide aggregate catch allocations?
- At what level of effort do individual species go below the 20% of B0 minimum biomass threshold?
- At what level of effort is revenue maximized for the species mix?
- Do individual fleets have different characteristics than the fleets acting together?
- Given the performance of individual fleets, can we begin to optimize fleet efforts to balance system-level yield (in tons and revenue) and species status?

Results

The first result of note is that both species interactions and environmental signals changed yield and the perception of stock status over time, even with constant fishing effort in the three fleets. A baseline run with no fishing effort showed several species (e.g. elasmobranchs, cod, flounders) initially increasing as would be expected with no fishing mortality, but other species (herring, mackerel, silver hake) declining because of increased predation mortality from higher unfished predator biomass (Figure 2). Dogfish, with the most K-selected life history, slightly but continuously increased under no fishing effort until later in the run in contrast to other predators which leveled off before year 20. Furthermore, some species declined towards the end of the 50-year run because of increasing bottom water temperature on Georges Bank causing increased predation mortality via the temperature-dependent consumption function in the model. This temperature increase alone results in ∼5% increase in predation mortality towards the end of the time period because of increased consumption in the simulation model, especially by large predators. Therefore, all runs were compared with the appropriate environmental baseline (year 20, cooler, or year 50, warmer) rather than assuming a constant equilibrium condition. To achieve this, year 20 yields and biomasses under alternate effort levels are compared with year 20 unfished biomass in the unfished baseline run for each ensemble member to calculate the appropriate B0. Similarly, year 50 yields and biomasses are compared with year 50 unfished biomass from the same unfished baseline run.

Individual species yield curves driven by incrementally increasing effort in all gears together showed a variety of shapes (Figure 3), with some species having clear peaks in yield while others did not under the current model configuration (in particular the fleet specific combinations of size selectivity and catchability by species). Similarly, some species approached or surpassed lower biomass thresholds over the range of trial effort levels while others increased (herring, mackerel) because of release from predation mortality (Figure 4.).

Analysis of aggregations including the full 10 species system and 4 aggregates combining foraging guild and taxonomy showed the potential for maximizing biomass and economic yields given the constraint that no species may drop below the specified biomass threshold of 20% of "ecosystem" unfished biomass. At the full 10 species system level for all fleets together, the yield curve was flat above ∼50% of average observed effort for both the cooler year 20 and warmer year 50 regime (Figure 5). At the level of the four aggregate groups, there were clear peaks in yield curves for Piscivores and Benthivores, while the yield for Pelagics and Elasmobranchs generally increased along with effort across all fleets (Figure 6).

There were trade-offs between yield, species status, and revenue across the range of simulated effort levels for all fleets combined. For example, while yield was maximal at the highest levels of simulated effort for the full 10-species system under year 20 conditions, these levels would not be permitted because several species fell below biomass thresholds. Up to 50% of average effort, median biomass for all species remained above 20% of B0, but at 100% of average effort, cod, yellowtail flounder, and winter flounder simulated biomass were all below the threshold (Figure 7c). Furthermore, revenue was highest at the lower effort levels because the species mix there was most valuable (Figure 7j). At low to moderate effort levels, simulated catch was relatively balanced between herring ($\$0.15\,\mathrm{lb}^{-1}$) and cod, haddock, and yellowtail flounder ($\$1.86$–$\$2.02\,\mathrm{lb}^{-1}$; Figure 7). At higher effort levels (100–150%), herring and haddock dominated the simulated catch but only haddock dominated the value.

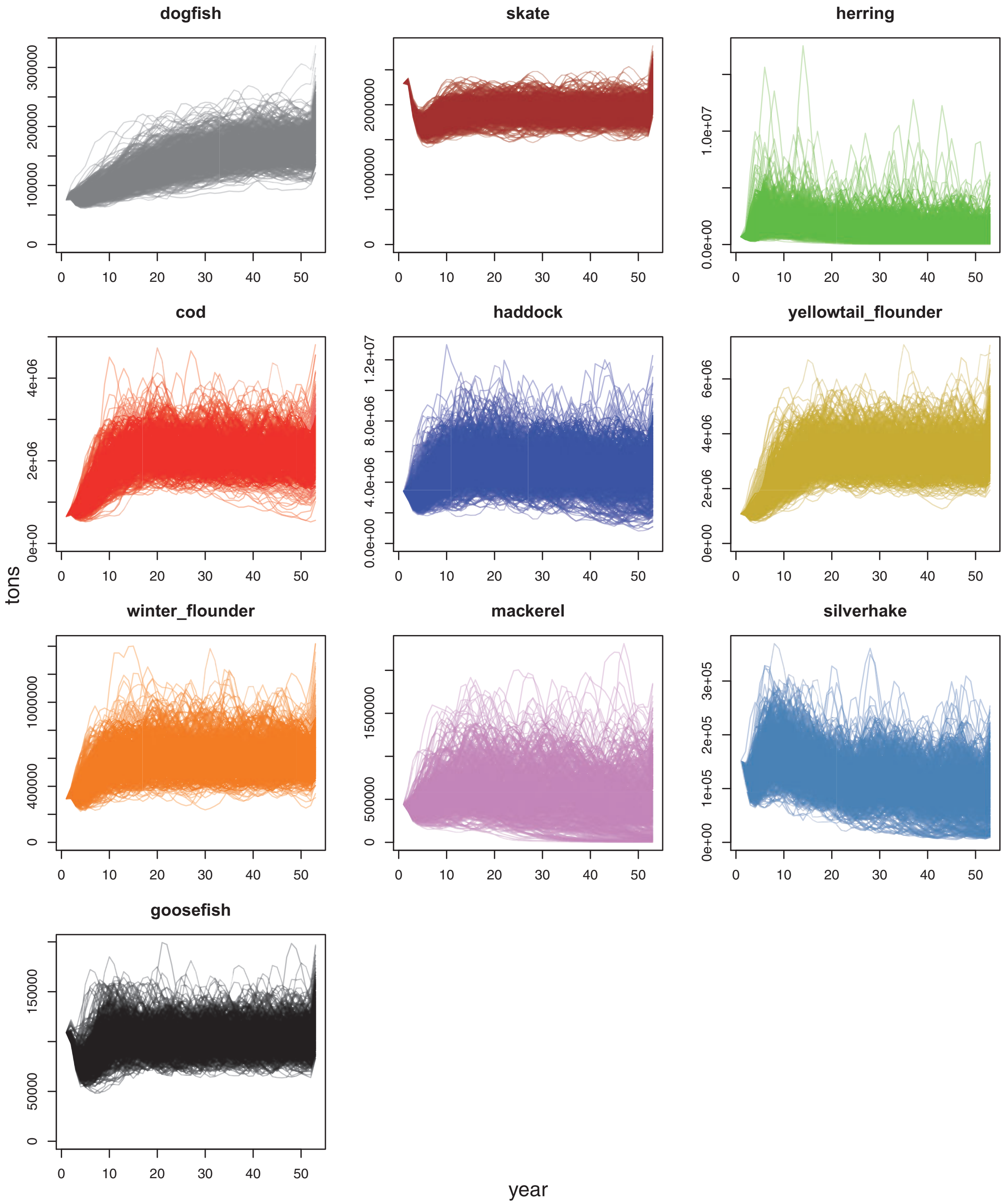

Figure 2. Simulated biomass (*t*) time series with no fishing in the 10-species system. Lines represent individual runs in the 500 run ensemble with stochastic recruitment variability.

Trade-offs between revenue and yield in tons were greater for the full 10 species system than within the aggregate catch groups (Table 2). The aggregate groups combined species with generally similar life histories and 2012 average prices. For all groups except Elasmobranchs, the maximum yield in revenue and tons were achieved at the same effort level with biomass of all species in the aggregate maintained above the threshold under both environmental regimes (Table 2). However, warmer year 50 environmental conditions did exacerbate trade-offs, with Elasmobranch maximum yields or revenue not achievable before species fell below the biomass threshold (partially because B0 for dogfish was higher in year 50 relative to year 20 because of their life history;

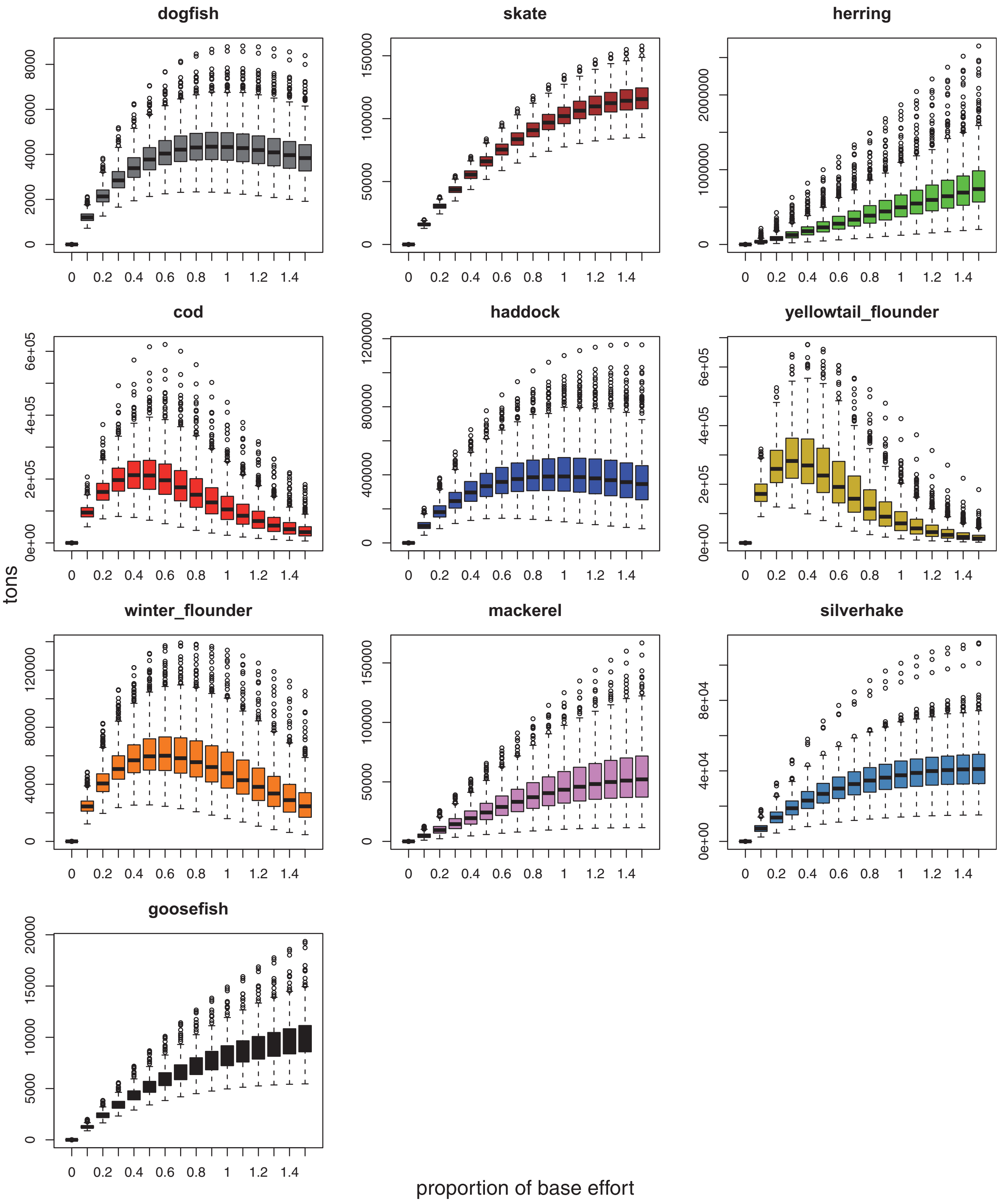

Figure 3. Yield in tons for each species and level of fishing effort (as a proportion of the base effort illustrated in Figure 1) for all fleets combined under year 20 environmental conditions. Boxes in this and all following figures represent the 50% interquantile range of the 500 runs at the fixed level of fishing effort, with the median indicated by a black line within the box.

even under changing environmental conditions they may not have fully rebounded from a fished condition until about year 35 of our simulation; Figure 2). Both the Elasmobranch and Planktivore groups had larger differences in results between environmental regimes across fleets than the Piscivore and Benthivore groups (values changed but shapes of yield curves did not). Piscivores and Benthivores were least resilient to high effort levels (Figure 6), reflecting in part the underlying contrast in the

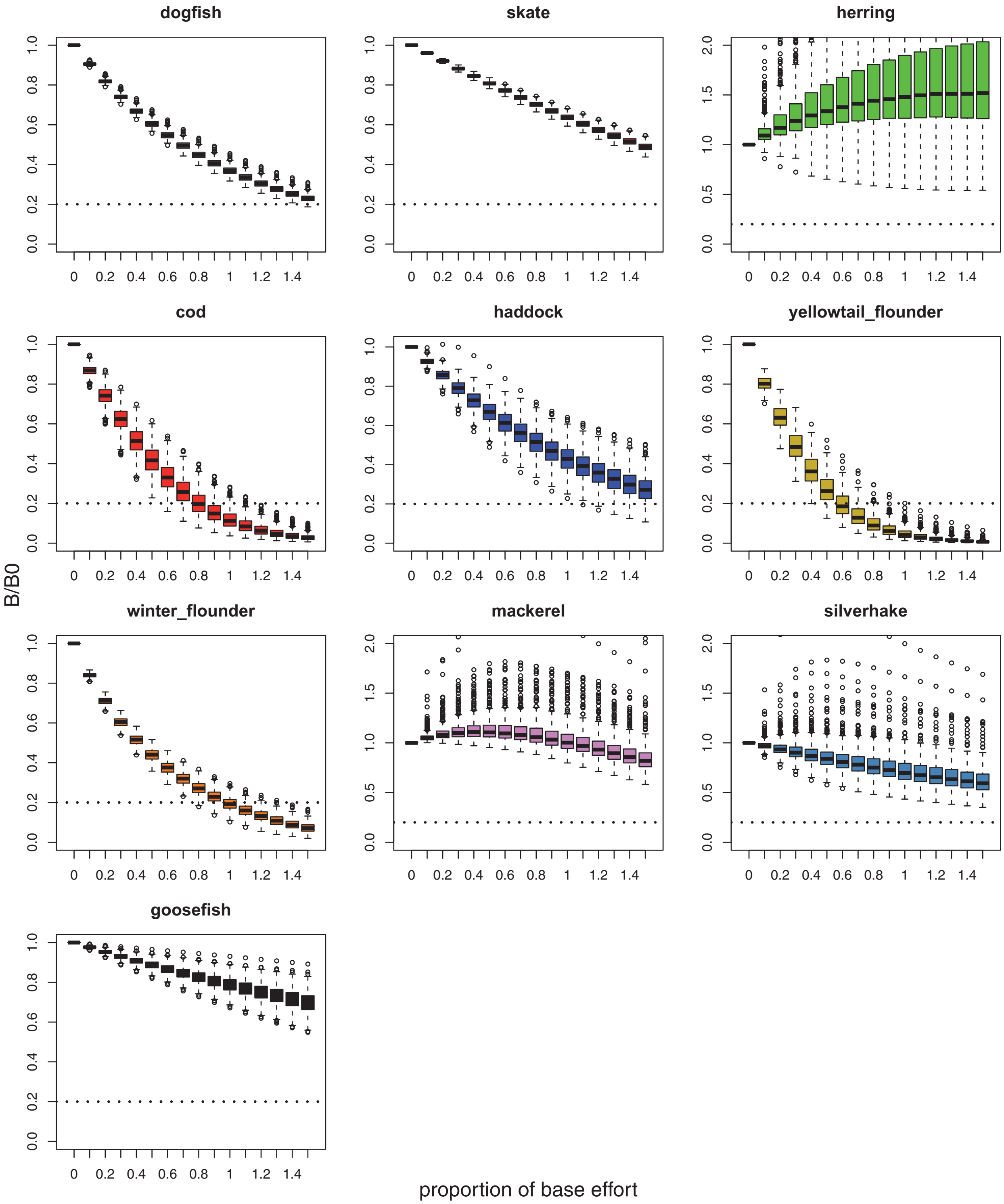

Figure 4. Ratio of fished biomass relative to unfished biomass for each species and level of fishing effort for all fleets combined under year 20 environmental conditions. Dotted lines indicate the biomass depletion threshold tested here: 20% of unfished biomass.

relatively high bottom trawl fleet effort directed at these groups relative to the lower effort in other fleets in these simulations.

Examining individual fleet yield curves revealed different trade-offs between species biomass status, yield, and revenue (Table 2), and suggested that alternative combinations of gears could result in ∼12% more system yield within the constraint that no species fall below 20% B0 under cooler year 20 conditions (Figure 8). However, this increase in yield was primarily from increased catch of herring, a relatively low-value species by weight. Therefore, the gains in revenue with the alternative combinations of effort by gear were minor (∼5%) in these simulations. Under year 50 conditions, the fixed gear effort optimized

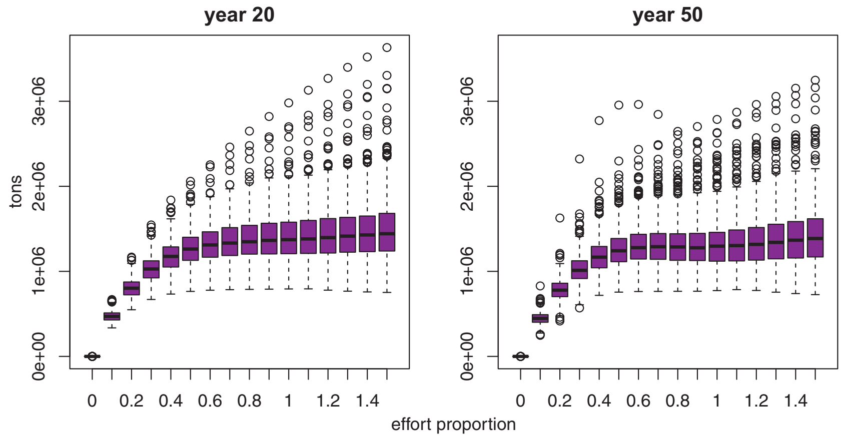

Figure 5. Yield in tons for the full 10 species system across a range of all fleets combined effort levels and under different environmental conditions: cooler year 20 (left panel) and warmer year 50 (right panel).

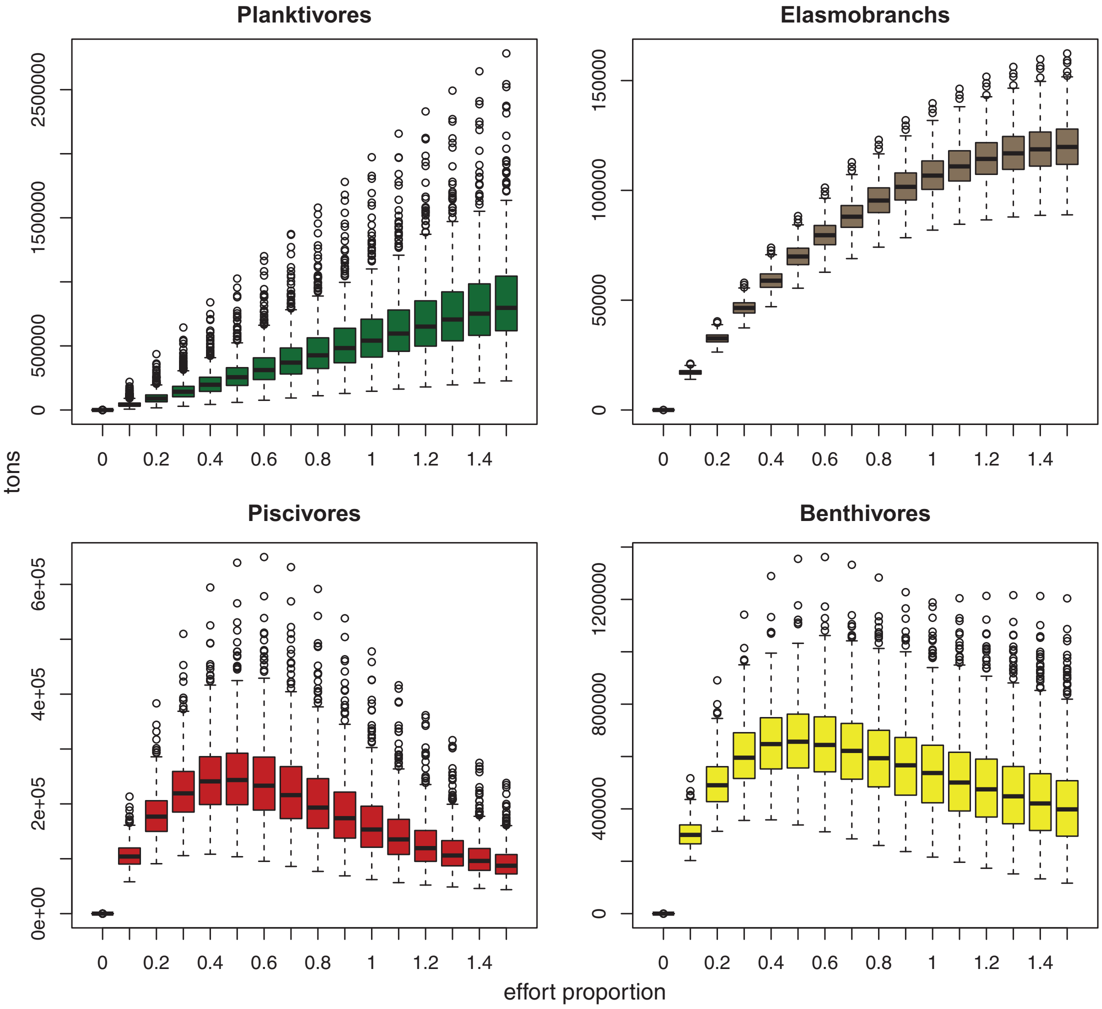

Figure 6. Yield in tons for each of the aggregate species groups across a range of all fleets combined effort levels and under cooler year 20 environmental conditions.

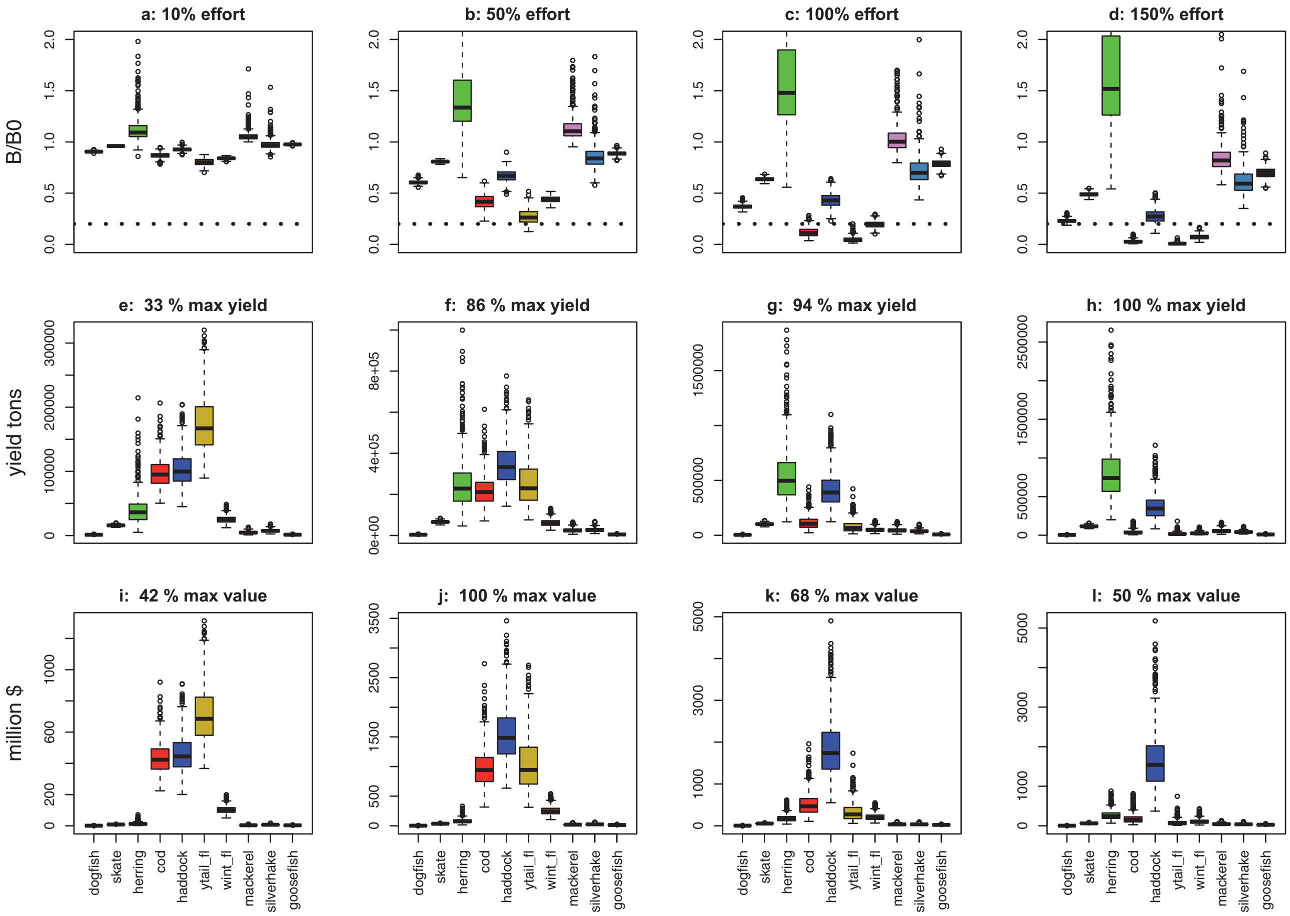

Figure 7. Results for biomass status (top row), yield in tons (middle row) and revenue (bottom row) for selected effort levels (columns: 10, 50, 100, and 150% of average in all fleets together) under the cooler year 20 environmental regime. Abbreviations: ytail_fl = yellowtail flounder; wint_fl = winter flounder. Individual plot titles for middle and bottom rows are percentages of maximum simulated catch tons and millions of dollars, respectively, summed across all species.

for year 20 conditions would not be allowable, as dogfish fell below the year 50 biomass threshold under these effort levels. Therefore, the OMP would require mechanisms for adjustment to both species life history and new environmental conditions over time. In addition, fleet selectivities and catchabilities would not be constant over time as in this simulation. This suggests that a clear understanding of fleet characteristics would be necessary to evaluate and update the OMP, but also that further optimization of yield and revenue could be achieved given appropriate incentives to alter fishing practices within each fleet.

Discussion

Worldwide, there is considerable interest in developing fishery management that balances social, economic, and ecological objectives for multispecies, multifleet fisheries (e.g. Sainsbury, 2000; Nordic Council of Ministers *et al.*, 2013; Möllmann *et al.*, 2014; Voss et al., 2014a, b; Trenkel *et al.*, 2015). Our results evaluate the trade-offs between management simplicity, yield, and biomass status for a 10 species, 3 fleet ecosystem loosely based on Georges Bank in the USA. Overall, we found that there are aggregate catch levels that can both maximize yield and revenue while conserving biomass of individual species, in compliance with current the US law. However, community composition and value trade-off over a range of fishing effort when considering the system as a whole. We consider this a "thought experiment" and a starting point for further discussion with scientists, managers, fishermen, and other stakeholders in the region. Below we discuss the performance of the management procedure in detail for this thought experiment. We conclude by identifying the next steps and analyses necessary to make an ecosystem-based multispecies management procedure operational.

Can the proposed management procedure achieve multiple objectives within the constraints?

- Is there a clear maximum yield to specify a total catch cap for the system?

The relatively flat 10-species yield curve for all gears combined suggests that there is no clear system level yield limit to be derived from this simulation. However, system level yield limits can be derived by other methods, such as the energetic constraint imposed by ecosystem primary production (e.g. Jennings *et al.*, 2008; Blanchard *et al.*, 2012). There are clear advantages to defining ecosystem catch limits independently of fishing fleet characteristics, so that all stakeholders have a better understanding of the thermodynamic and biological limits of ecosystem production and can scale expectations accordingly.

Table 2. Biomass status (all species above minimum stock biomass above threshold = green/darker gray; at least one below threshold = orange/lighter gray) for each fleet, effort level, and environmental regime, with the effort corresponding to maximum median yield in tons (Y) and revenue ($).

		Effort proportion relative to average																													
		Year 20 environment																Year 50 environment															
Fleet	**Species group**	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
all	planktivores	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y
	elasmobranchs	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧 $,Y	🟧
	piscivores	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	benthivores	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	full system	🟩	🟩	🟩	🟩	🟩	🟩 $	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 Y	🟩	🟩	🟩	🟩	🟩	🟩 $	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 Y
bottom only	planktivores	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $Y
	elasmobranchs	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 Y	🟩 $	🟩
	piscivores	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	benthivores	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩 $	🟩 Y	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	full system	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
fixed only	planktivores	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	elasmobranchs	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧 $,Y
	piscivores	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y
	benthivores	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y
	full system	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧 $,Y
pelagic only	planktivores	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟩	🟩	🟩 $,Y	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	elasmobranchs	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y
	piscivores	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $Y	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	benthivores	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 $,Y
	full system	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 Y	🟩	🟩	🟩	🟧	🟧 $	🟧	🟧	🟩	🟩	🟩 Y	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 $

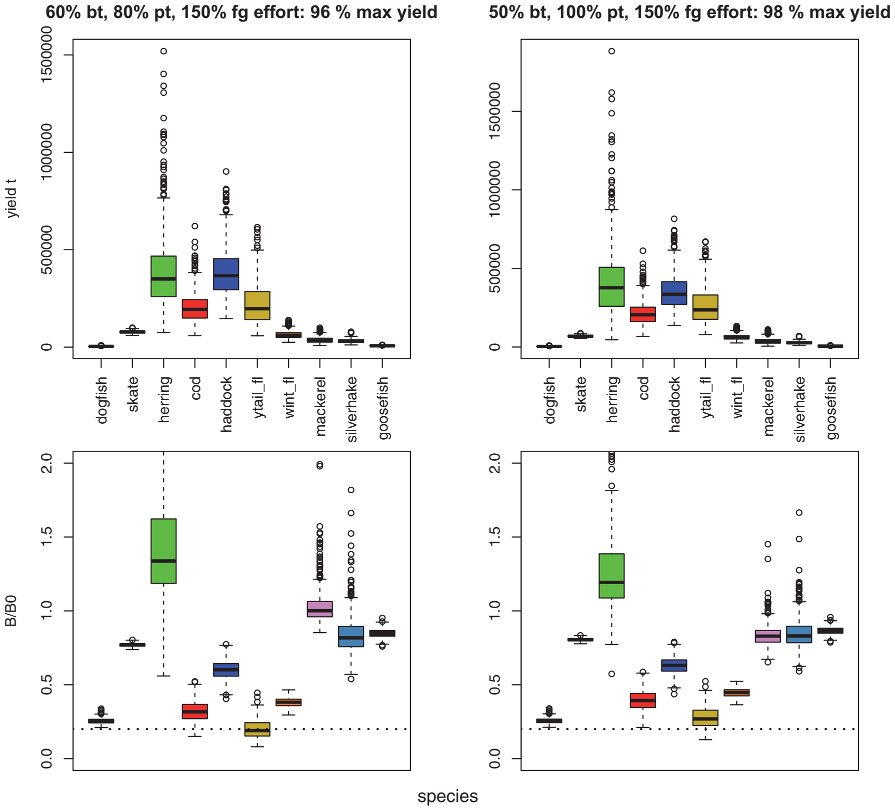

Figure 8. Simulated yield and biomass status under cooler year 20 conditions using two alternative mixes of fleet effort: a combination of 60% bottom trawl (bt), 80% pelagic trawl (pt), and 150% fixed gear (fg) relative to average observed effort in each gear type (left panel) and a combination of 50% bottom trawl, 100% pelagic trawl, and 150% fixed gear (right panel). Abbreviations: ytail_fl = yellowtail flounder; wint_fl = winter flounder. Plot titles also show total yield summed across all species under these mixes as a percentage of the (unattainable) maximum yield for all gears combined.

- Are there clear yield maxima for aggregate species groups to guide aggregate catch allocations?

Yield maxima were found only for a subset of the species and aggregate groups in this simulation. Further analysis could clarify whether higher levels of efforts in the fixed gear and pelagic fisheries would be feasible and worth exploring to find an effort level where yields had a clear maximum for the Planktivore and elasmobranch aggregates. An alternative approach would be to use aggregate production models to estimate aggregate fishing mortality based reference points (e.g. Lucey *et al.*, 2012) with some consideration of fleet catch composition retained. The main point of having multispecies catch limits is to set annual limits at a level of aggregation that relies less on precise estimation of individual species' potentially changing mortality and production (Legault and Palmer, 2015). The advantage should be in reducing the number of catch limits to streamline management and allow fishermen a higher degree of flexibility than exists with multiple interacting catch limits. This would require a careful balance of incentives to ensure that individual species are not overharvested within the aggregate catch limit, a recognized problem with managing species complexes (Methot *et al.*, 2014).

- At what level of effort do individual species go below the 20% of B0 minimum biomass threshold?

For the aggregate species groups (but not the full 10-species system), highest yields in both tons and revenue were achieved without depleting any species below the biomass threshold in this simulation. While this is a promising result, suggesting that catch limits specified for aggregate groups may be "safe" for individual species, it is dependent on the fishing fleet characteristics specified in the simulation. Additional testing with a wider variety of fleet characteristics (as well as alternative biomass thresholds more tailored to species life history) is necessary to establish the robustness of this result. Similarly, including more sensitive species than dogfish within an aggregate might constrain overall catches unless fleets were able to avoid them. Furthermore, the proposed management still requires an initial assessment of individual species biomass-based reference points. Although most US fisheries use biomass limit reference points based on MSY, we used an unfished biomass limit reference point because "unfished" can be defined simply at the ecosystem or multispecies level, whereas MSY for a given species in a multispecies context is conditional on the management and status of all interacting species in the system (Collie and Gislason, 2001). While we evaded the complexity of multispecies MSY using a proportion of unfished biomass as a threshold, unfished biomass at the ecosystem level is no easier to estimate in reality. Often, simply "turning off fishing" in an ecosystem model does not result in fished groups returning to levels of biomass capable of supporting high historical catches (Gaichas *et al.*, 2011), suggesting that estimating unfished biomass requires assumptions about changing productivity over time. Here, we used snapshots in time to address non-stationary processes potentially affecting biomass reference points, but the mix of interacting species with different life histories still means that a single snapshot in time does not ensure similar status even within a no-fishing simulation, as we observed for dogfish. Therefore, further exploration of biomass limit reference points would be useful in developing OMPs. Similarly, monitoring of individual species to ensure that the stock remains above the reference level is also required. This could be achieved using fishery independent survey indices (which would require testing along with other components of the management strategy) or with occasional model-based assessments. Catch limits under this strategy are still ultimately constrained by the status of the "weakest" stock, a clear difficulty with current management (Methot *et al.*, 2014), so contingency plans for weak or recovering stocks within aggregate groups, including possibly technical and spatial measures to decouple mortality rates, require development and simulation testing as well.

- At what level of effort is revenue maximized for the species mix?

Our extremely simple revenue analysis indicated few trade-offs between yield in tons and value for the aggregate groups, but larger trade-offs at the full system level because of both changing species interactions as effort increased and differences in value between the relatively high yield Planktivores and the higher valued but more vulnerable Piscivores and Benthivores. We consider this only a first attempt at incorporating economic information and objectives. While we examined trade-offs under changing environmental conditions, consideration of changing economic conditions is required as well—ex vessel value for a species would not remain constant for a 50-year period, or for substantial shifts in landings. Additionally, considering the costs of fishing would provide for both a better estimate of economic value and allow for a more rigorous comparison across scenarios. Ultimately, much more sophisticated methods can be applied to evaluate trade-offs between risk and economic returns in a multispecies system, and the underlying species interactions can also be considered as well (Edwards *et al.*, 2004; Sanchirico *et al.*, 2008; Jin *et al.*, 2016). In addition, other social and economic objectives could be incorporated (e.g. employment, safety at sea, regional seafood preferences).

- Do individual fleets have different characteristics than the fleets acting together?

Yes, some demonstrate options that would be counterproductive such as fishing with only pelagic gear (primarily targeting schooling forage species) while allowing predator populations to rebuild without fishing pressure, thus further increasing mortality on the fished forage species. However, we note that this model does not include the effect of decreased prey populations on predator growth, so predator populations may be more constrained by poor growth under these conditions than this simulation model suggests.

- Given the performance of individual fleets, can we begin to optimize fleet efforts to balance system-level yield (in tons and value) and species status?

We showed that some increase in both catch and value is possible within the constraints given the current simulation model parameterization. The key to developing and using an OMP based on multispecies, multifleet fisheries will be defining the fishing fleets realistically in terms of species and size selectivity, and also in defining each fleet's capacity to change these properties in response to both environmental changes and management requirements. Fishermen are extraordinarily capable of adapting to changing conditions. This capacity can result in fewer trade-offs than are implied by this preliminary analysis if management incentives to encourage or restrict the catch of certain species or groups are aligned with economic and social objectives.

Next steps in developing an ecosystem-based OMP

To explore the performance of the management strategy itself, we assumed a "perfect knowledge" integrated multispecies stock assessment existed to evaluate the status of aggregate species groups and individual species. In reality, perfect knowledge of stock status and catch is obviously unrealistic. However, the intention here was not to evaluate a stock assessment method, but rather to determine whether the strategy might achieve basic catch and value objectives under single species stock status constraints in a relatively simple system. For OMPs, the assessment methods require evaluation along with data inputs and management strategies. Assessment model performance testing is a critical and growing area of research (e.g. Deroba *et al.*, 2015). Multispecies models show considerable promise for use in operational assessment because they can produce similar outputs to currently used single species assessment models (Plagányi *et al.*, 2014; Collie *et al.*, 2016). Performance evaluation for multispecies assessment models has been initiated (Curti *et al.*, 2013; Van Kirk *et al.*, 2015), and requires expansion. The next steps will be to integrate a more realistic assessment process where observation error, model structural uncertainty, and other assessment uncertainties are included and evaluated to determine how they affect the robustness of the management procedure. Multi-model ensemble methods can address model structural uncertainty (e.g. Ianelli *et al.*, 2015), and should be evaluated by simulation testing as well. The influence of changing environmental conditions on multispecies interactions and resulting reference points must be retained and expanded (e.g. Holsman *et al.*, 2015).

Similarly, an OMP would require testing with full feedback between the simulated ecosystem and the set of management measures within a full Management Strategy Evaluation (MSE) process (Punt *et al.*, 2014b). We primarily evaluated whether the proposed OMP could meet multiple objectives subject to the individual species conservation constraint. We took steps towards "closed loop" evaluation for two candidate combinations of fishing effort levels that might minimize trade-offs between objectives, finding that a combination designed for one set of environmental conditions would fail under warmer conditions. A much broader evaluation of feedbacks between multispecies catch limits, economic value, fleet characteristics, and ecological dynamics is necessary to follow up on this initial analysis. The interaction of these feedbacks and uncertainties in the system also needs further exploration. Ideally, a broad range of uncertainties would be identified along with stakeholders in an interactive MSE process, and could lead to the specification of multiple operating models (Plagányi *et al.*, 2007). As scientists, we identified some sources of error, but the list is not exhaustive. Process error was included here with 500 different draws from stock-recruitment functions. Non-stationarity was included in predation mortality because of the temperature signal's effect on consumption. Further uncertainty driven by climate change could be introduced for this particular ecosystem where temperature is rising quickly (Friedland and Hare, 2007), and changes in secondary production, recruitment, and species distributions have already been observed (e.g. Nye *et al.*, 2009; Lucey and Nye, 2010; Groger and Fogarty, 2011; Hare *et al.*, 2012; Friedland *et al.*, 2013). In reality, it may be difficult to distinguish these signals given the additional observation error and assessment error described above, but the main objective would be to evaluate the procedure's robustness to these uncertainties in meeting stated management objectives (Punt *et al.*, 2014a).

Finally, and most importantly, management objectives need to be defined and clearly specified by stakeholders involved in the multispecies fishery to define an OMP (Plagányi *et al.*, 2007; Rademeyer *et al.*, 2007; Trenkel *et al.*, 2015). The objectives we present here are drawn from both the US legal frameworks and experience with the regional management process to serve as an example to start discussion, although in particular the biomass limit reference points and risks of exceeding them would require further development for different life history types. Furthermore, the management strategy presented here is just one of many potential management strategies that could be used to achieve similar objectives. In an EBFM context, additional objectives related to conserving non-target species status either by limiting bycatch (e.g. Shephard *et al.*, 2015) or maintaining trophic pathways (e.g. Begoña Santos *et al.*, 2014), and further trade-offs between these objectives (e.g. Fay *et al.*, 2015; Smith *et al.*, 2015), could be considered. The desired probability of achieving an objective or avoiding a threshold would also need to be specified by stakeholders. Our results could be used to further evaluate whether median values or some other quantile of results would be most appropriate in specifying performance metrics. However, these scientist-supplied objectives and performance metrics cannot substitute for objectives that would be defined within an inclusive stakeholder process (which includes scientists, managers, fishermen, and other resource users). Developing effective processes to bring stakeholders together for MSE may be the most important step for achieving operational ecosystem-based fisheries management procedures.

Supplementary data

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

Acknowledgements

We are grateful to the EU MYFISH Project for providing travel funding for SG to participate as an external partner in multiple workshops from 2012 to 2015, including the ICES MYFISH Symposium "Targets and Limits for Long-Term Fisheries Management." Geret DiPiper improved this work with many discussions and comments, and the constructive comments of the editor and an anonymous reviewer further improved the manuscript.

References

Begoña Santos, M., Saavedra, C., and Pierce, G. J. 2014. Quantifying the predation on sardine and hake by cetaceans in the Atlantic waters of the Iberian peninsula. Deep Sea Research Part II: Topical Studies in Oceanography 106: 232–244.

Blanchard, J. L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J. I., Holt, J. *et al.* 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philosophical Transactions of the Royal Society of London B: Biological Sciences 367: 2979–2989.

Brown, B. E., Brennan, J. A., Grosslein, M. D., Heyerdahl, E. G., and Hennemuth, R. C. 1976. The effect of fishing on the marine finfish biomass in the northwest Atlantic from the Gulf of Maine to Cape Hatteras. ICNAF Research Bulletin 12: 49–68.

Collie, J. S., Botsford, L. W., Hastings, A., Kaplan, I. C., Largier, J. L., Livingston, P. A., Plagányi, É. *et al.* 2016. Ecosystem models for fisheries management: finding the sweet spot. Fish and Fisheries 17: 101–125.

Collie, J. S., and Gislason, H. 2001. Biological reference points for fish stocks in a multispecies context. Canadian Journal of Fisheries and Aquatic Sciences 58: 2167–2176.

Curti, K. L., Collie, J. S., Legault, C. M., Link, J. S., and Hilborn, R. 2013. Evaluating the performance of a multispecies statistical catch-at-age model. Canadian Journal of Fisheries and Aquatic Sciences 70: 470–484.

Degnbol, P., and McCay, B. J. 2007. Unintended and perverse consequences of ignoring linkages in fisheries systems. ICES Journal of Marine Science 64: 793–797.

Deroba, J. J., Butterworth, D. S., Methot, R. D., Oliveira, J. A. A. D., Fernandez, C., Nielsen, A., Cadrin, S. X. *et al.* 2015. Simulation testing the robustness of stock assessment models to error: some results from the ICES strategic initiative on stock assessment methods. ICES Journal of Marine Science 72: 19–30.

Edwards, S. F., Link, J. S., and Rountree, B. P. 2004. Portfolio management of wild fish stocks. Ecological Economics 49: 317–329.

Fay, G., Link, J. S., Large, S. I., and Gamble, R. J. 2015. Management performance of ecological indicators in the Georges Bank finfish fishery. ICES Journal of Marine Science 72: 1285–1296.

Fogarty, M. J. 2013. The art of ecosystem-based fishery management. Canadian Journal of Fisheries and Aquatic Sciences 71: 479–490.

Fogarty, M. J., and Murawski, S. A. 1998. Large-scale disturbance and the structure of marine systems: fishery impacts on Georges Bank. Ecological Applications 8: S6–S22.

Fournier, D. A., Skaug, H. J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M. N., Nielsen, A. *et al.* 2012. AD model builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods and Software 27: 233–249.

Friedland, K. D., Kane, J., Hare, J. A., Lough, R. G., Fratantoni, P. S., Fogarty, M. J., and Nye, J. A. 2013. Thermal habitat constraints on zooplankton species associated with Atlantic cod (*Gadus morhua*) on the US Northeast Continental Shelf. Progress in Oceanography 116: 1–13.

Friedland, K., and Hare, J. 2007. Long-term trends and regime shifts in sea surface temperature on the Continental Shelf of the northeast United States. Continental Shelf Research 27:

Gabriel, W. L., and Mace, P. M. 1999. A review of biological reference points in the context of the precautionary approach. *In* Proceedings of the fifth national NMFS stock assessment workshop: providing scientific advice to implement the precautionary approach under the Magnuson-Stevens fishery conservation and management act. NOAA Tech Memo NMFS-F/SPO-40, pp. 34–45. http://oarfish.nmfs.noaa.gov/StockAssessment/workshop_documents/nsaw5/gabriel_.pdf (last accessed 21 January 2016).

Gaichas, S., Gamble, R., Fogarty, M. J., Benoit, H., Essington, T., Fu, C., Koen-Alonso, M. *et al.* 2012. Assembly rules for aggregate-species production models: simulations in support of management strategy evaluation. Marine Ecology Progress Series 459: 275–292.

Gaichas, S. K., Aydin, K. Y., and Francis, R. C. 2011. What drives dynamics in the Gulf of Alaska? Integrating hypotheses of species, fishing, and climate relationships using ecosystem modeling. Canadian Journal of Fisheries and Aquatic Sciences 68: 1553–1578.

Geromont, H. F., and Butterworth, D. S. 2015. Complex assessments or simple management procedures for efficient fisheries management: a comparative study. ICES Journal of Marine Science 72: 262–274.

Groger, J. P., and Fogarty, M. J. 2011. Broad-scale climate influences on cod (*Gadus morhua*) recruitment on Georges Bank. ICES Journal of Marine Science 68: 592–602.

Hall, S. J., Collie, J. S., Duplisea, D. E., Jennings, S., Bravington, M., and Link, J. 2006. A length-based multispecies model for evaluating community responses to fishing. Canadian Journal of Fisheries and Aquatic Sciences 63: 1344–1359.

Hare, J. A., Morrison, W. E., Nelson, M. W., Stachura, M. M., Teeters, E. J., Griffis, R. B., Alexander, M. A. *et al.* 2016. A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. Continental Shelf. PLoS One 11: e0146756.

Hare, J. A., Wuenschel, M. J., and Kimball, M. E. 2012. Projecting range limits with coupled thermal tolerance - climate change models: an example based on gray snapper (*Lutjanus griseus*) along the U.S. east coast. PLoS One 7: e52294.

Hobday, A. J., and Pecl, G. T. 2013. Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. Reviews in Fish Biology and Fisheries 24: 415–425.

Holsman, K. K., Ianelli, J., Aydin, K., Punt, A. E., and Moffitt, E. A. 2015. A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models. *Deep Sea Research Part II: Topical Studies in Oceanography*. http://www.sciencedirect.com/science/article/pii/S0967064515002751 (last accessed 12 November 2015).

Ianelli, J., Holsman, K. K., Punt, A. E., and Aydin, K. 2015. Multimodel inference for incorporating trophic and climate uncertainty into stock assessments. *Deep Sea Research Part II: Topical Studies in Oceanography*. http://www.sciencedirect.com/science/article/pii/S0967064515001058 (last accessed 18 December 2015).

Jennings, S., Melin, F., Blanchard, J. L., Forster, R. M., Dulvy, N. K., and Wilson, R. W. 2008. Global-scale predictions of community and ecosystem properties from simple ecological theory. Proceedings of the Royal Society B 275: 1375–1383.

Jin, D., DePiper, G., and Hoagland, P. 2016. An empirical analysis of portfolio management as a tool for implementing ecosystem-based fishery management. North American Journal of Fisheries Management 36: 652–669.

Legault, C. M., and Palmer, M. C. 2015. In what direction should the fishing mortality target change when natural mortality increases within an assessment? Canadian Journal of Fisheries and Aquatic Sciences 73: 349–357.

Link, J. S. 2010. Ecosystem-based Fisheries Management: Confronting Tradeoffs. Cambridge University Press, Cambridge, UK.

Lucey, S. M., Cook, A. M., Boldt, J. L., Link, J. S., Essington, T. E., and Miller, T. J. 2012. Comparative analyses of surplus production dynamics of functional feeding groups across 12 northern hemisphere marine ecosystems. Marine Ecology Progress Series 459: 219–229.

Lucey, S. M., and Nye, J. A. 2010. Shifting species assemblages in the Northeast US Continental Shelf Large Marine Ecosystem. Marine Ecology Progress Series 415: 23–33.

Mace, P. M. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. Canadian Journal of Fisheries and Aquatic Sciences 51: 110–122.

Magnússon, K. G. 1995. An overview of the multispecies VPA — theory and applications. Reviews in Fish Biology and Fisheries 5: 195–212.

Methot, R. D., Tromble, G. R., Lambert, D. M., and Greene, K. E. 2014. Implementing a science-based system for preventing overfishing and guiding sustainable fisheries in the United States. ICES Journal of Marine Science 71: 183–194.

Möllmann, C., Lindegren, M., Blenckner, T., Bergström, L., Casini, M., Diekmann, R., Flinkman, J., *et al.* 2014. Implementing ecosystem-based fisheries management: from single-species to integrated ecosystem assessment and advice for Baltic Sea fish stocks. ICES Journal of Marine Science 71: 1187–1197.

Murawski, S. 2000. Definitions of overfishing from an ecosystem perspective. ICES Journal of Marine Science 57: 649–658.

National Marine Fisheries Service. 2014. Fisheries Economics of the United States, 2012. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-F/SPO-137. Economics and Social Analysis Division, Office of Science and Technology, National Marine Fisheries Service, Silver Spring, MD. https://www.st.nmfs.noaa.gov/Assets/economics/documents/feus/2012/FEUS2012.pdf (last accessed 25 January 2016).

National Marine Fisheries Service. 2015. Fisheries of the United States, 2014. U.S. Department of Commerce, NOAA Current Fishery Statistics No. 2014. http://www.st.nmfs.noaa.gov/commercial-fisheries/fus/fus14/index (last accessed 29 January 2016).

NEFSC. 2012. Ecosystem Status Report for the Northeast Shelf Large Marine Ecosystem-2011. US Dept Commer, Northeast Fish Sci Cent Ref Doc.12-07. National Marine Fisheries Service, 166 Water Street, Woods Hole, MA. http://www.nefsc.noaa.gov/nefsc/publications/crd/crd1207/ (last accessed 25 June 2016).

NEFSC, EAP. 2015. Northeast Fisheries Science Center Ecosystem Considerations. http://www.nefsc.noaa.gov/ecosys/ (last accessed 25 September 2015).

Nordic Council of Ministers, Rindorf, A., Schmidt, J., Bogstad, B., Reeves, S., and Walther, Y. 2013. A Framework for Multispecies Assessment and Management. Nordic Council of Ministers. http://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-798 (last accessed 20 January 2016).

Nye, J. A., Link, J. S., Hare, J. A., and Overholtz, W. J. 2009. Changing spatial distribution fish stocks in relation to climate and population size within the Northeast US continental shelf. Marine Ecology Progress Series 393: 111–129.

Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., Dayton, P. *et al.* 2004. Ecosystem-based fishery management. Science 305: 346–347.

Plagányi, ÉE., Punt, A. E., Hillary, R., Morello, E. B., Thébaud, O., Hutton, T., Pillans, R. D. *et al.* 2014. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. Fish and Fisheries 15: 1–22.

Plagányi, ÉE., Rademeyer, R. A., Butterworth, D. S., Cunningham, C. L., and Johnston, S. J. 2007. Making management procedures operational—innovations implemented in South Africa. ICES Journal of Marine Science 64: 626–632.

Punt, A. E., A'mar, T., Bond, N. A., Butterworth, D. S., Moor, C. L., de Oliveira J. A. A. D., Haltuch, M. A. *et al.* 2014a. Fisheries management under climate and environmental uncertainty: control rules and performance simulation. ICES Journal of Marine Science 71: 2208–2220.

Punt, A. E., Butterworth, D. S., de Moor C. L., de Oliveira J. A. A., and Haddon, M., 2014b. Management strategy evaluation: best practices. Fish and Fisheries 17: 303–334.

Punt, A. E., Smith, A. D. M., Smith, D. C., Tuck, G. N., and Klaer, N. L. 2014c. Selecting relative abundance proxies for BMSY and BMEY. ICES Journal of Marine Science 71: 469–483.

Rademeyer, R. A., Plagányi, ÉE., and Butterworth, D. S. 2007. Tips and tricks in designing management procedures. ICES Journal of Marine Science 64: 618–625.

Rochet, M. J., Collie, J. S., Jennings, S., and Hall, S. J. 2011. Does selective fishing conserve community biodiversity? Predictions from a length-based multispecies model. Canadian Journal of Fisheries and Aquatic Sciences 68: 469–486.

Sainsbury, K. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. ICES Journal of Marine Science 57: 731–741.

Sanchirico, J. N., Smith, M. D., and Lipton, D. W. 2008. An empirical approach to ecosystem-based fishery management. Ecological Economics 64: 586–596.

Shephard, S., Reid, D. G., Gerritsen, H. D., and Farnsworth, K. D. 2015. Estimating biomass, fishing mortality, and 'total allowable discards' for surveyed non-target fish. ICES Journal of Marine Science 72: 458–466.

Smith, A. D. M. 1994. Management strategy evaluation – the light on the hill. *In* Population dynamics for fisheries management, pp. 249–253. Ed. by D. A. Hancock. Australian Society for Fish Biology, Perth, Australia.

Smith, L., Gamble, R., Gaichas, S., and Link, J. 2015. Simulations to evaluate management trade-offs among marine mammal consumption needs, commercial fishing fleets and finfish biomass. Marine Ecology Progress Series 523: 215–232.

Trenkel, V. M., Hintzen, N. T., Farnsworth, K. D., Olesen, C., Reid, D., Rindorf, A., Shephard, S. *et al.* 2015. Identifying marine pelagic ecosystem management objectives and indicators. Marine Policy 55, 23–32.

Van Kirk, K. F., Quinn, T. J., Collie, J. S., and A'mar, Z. T. 2015. Assessing uncertainty in a multispecies age-structured assessment framework: the effects of data limitations and model assumptions. Natural Resource Modeling 28: 184–205.

Voss, R., Quaas, M. F., Schmidt, J. O., Tahvonen, O., Lindegren, M., and Möllmann, C. 2014a. Assessing social – ecological trade-offs to advance ecosystem-based fisheries management. PLoS ONE 9: e107811.

Voss, R., Quaas, M., Schmidt, J., and Hoffmann, J. 2014b. Regional trade-offs from multi-species maximum sustainable yield (MMSY) management options. Marine Ecology Progress Series 498: 1–12.

Handling editor: Raúl Prellezo