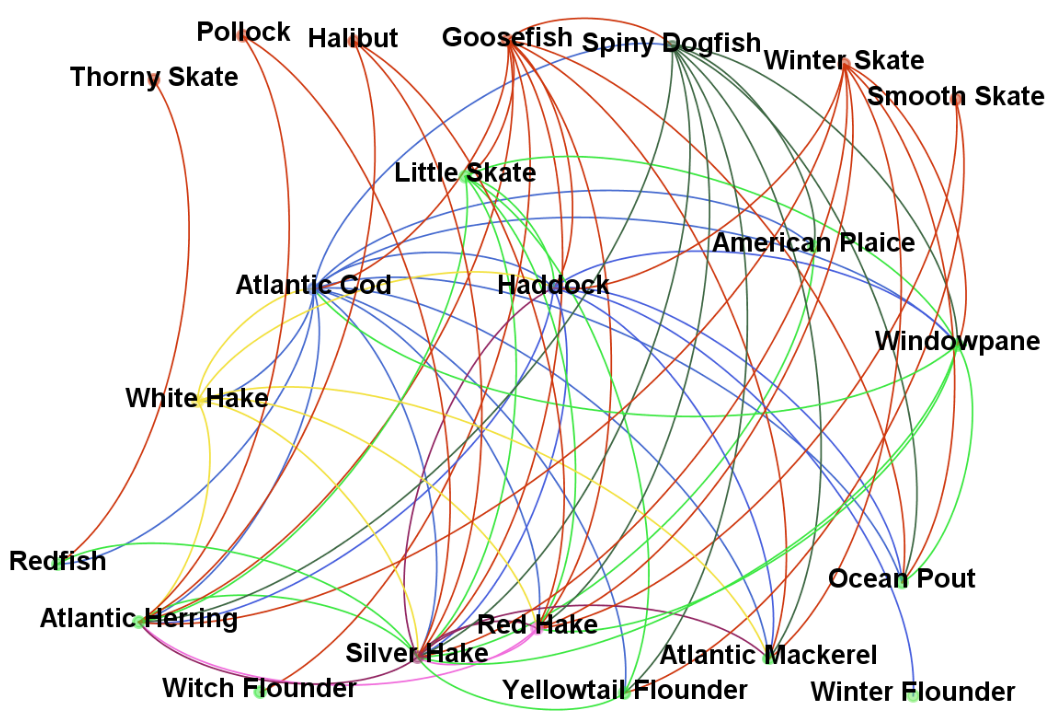
NEW ENGLAND FISHERY MANAGEMENT COUNCIL

DRAFT: Example application of operating models for Georges Bank ecosystem production unit (EPU) strategy evaluation)

prepared by the

Ecosystem Based Fishery Management Plan Development Team



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Simulation Tests

In the following, we describe the development of simulation models for testing management procedures designed to address the fundamental issues defined above. Technical details for the two models used in this demonstration can be found in the Appendix to this report. The principal elements of the proposed ecosystem-based management procedure include:

1) Establishing a Ceiling (or caps) to limit total removals from the ecosystem based on productivity characteristics,
2) partition this system wide Ceiling among defined Species Complexes (described below),
3) Maintain species complex and/or individual species above minimum stock size Floors (or lower thresholds) and
4) define multispecies harvest control rules and optimization procedures to implement elements 1-3 above to define an Operational Management Procedure (OPM).

This structure dictates that ecosystem overfishing criteria are applied at the ecosystem and species complex levels while the ecosystem equivalent of overfished criteria apply to individual species within the Species Complex.

Here, we identify Fishery Functional Groups as one avenue to objectively define Species Complexes. Management applied at this level is intended to simplify management in a way that embodies the dual role that individual species play in fishery ecosystems as human prey and as predators and prey in the food web. Fishery Functional Groups are framed by the intersection of fishery structure and practice with the role played by species within an ecosystem. We define a Fishery Functional Group (FFG) as species that are caught together by specified fleet sectors and that play similar roles in the ecosystem with respect to energy transfer. Because the species are caught together, inter alia they share similar habitat use patterns and also size structures related to specific selectivity characteristics of the fishing gears employed. The concept accordingly encapsulates information on the catch characteristics and targeting practices of different fleet sectors and fundamental ecological characteristics of assemblages of exploited species within these operational fisheries.

To illustrate how stock complexes based on fishery functional groups could be used in management, we develop a case study based on characteristics of the Georges Bank fishery ecosystem. We first focus on a ten species subsystem of the whole, Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), silver hake (*Merluccius bilinearis*), winter flounder (*Pseudopleuronectes americanus*), yellowtail flounder (*Limanda ferruginea*), monkfish (*Lophius americanus*), spiny dogfish (*Squalus acanthias*), winter skate (*Leucoraja ocellata*), Atlantic herring (*Clupea harengus*), and Atlantic mackerel (*Scomber scombrus*). Although their relative rankings have changed over time, these ten species have consistently ranked in the upper 10% of the fish species harvested on the bank in terms of catch and landed value. They are exploited by three dominant fleet sectors, each targeting different elements of the Georges Bank fish community

Below, we describe the details of two operating models that have been developed to provide preliminary tests of the elements of this approach and potential application in full Management Strategy Evaluation (MSE) should the Floors and Ceilings approach be deemed of sufficient interest for further formal examination by the Council. This work is undertaken with the recognition that if an MSE is undertaken by the council, the models may need further refinement and adjustment (or indeed replacement) to address the specific goals and objectives identified by stakeholders.

We first describe how we have defined Species Complexes as foci for management and for the specification of catch advice. We then turn to the elements of a length-based, multispecies-multifleet model, Hydra, (Gaichas et al. 2016) to test the fundamental elements of the Floors and Ceilings approach. To further explore formal approaches to optimization based on the tenets of portfolio theory (Edwards et al. 198x; Sanchirico et al. 20xx; Jin et al. (2016), We employ a simpler operating model, Kraken, based on the multispecies production model developed by Gamble and Link (20vv). Kraken does not incorporate size or age structure but does incorporate different forms of predation and competition in fish communities. The optimization routine is computationally intensive and we therefore elected to employ a simpler operating model for this phase of the analysis.

Species Complexes

The Species Complex concept is intended to simplify management in a way that embodies the dual role that individual species play in fishery ecosystems as human prey and as predators and prey in the food web. Fishery Functional Groups are framed by the intersection of fishery structure and practice with the role played by species within an ecosystem. We define a Fishery Functional Group (FFG) as species that are caught together by specified fleet sectors and that play similar roles in the ecosystem with respect to energy transfer. Because the species are caught together, inter alia they share similar habitat use patterns and also size structures related to specific selectivity characteristics of the fishing gears employed. The concept accordingly encapsulates information on the catch characteristics and targeting practices of different fleet sectors and fundamental ecological characteristics of assemblages of exploited species within these operational fisheries.

We based our characterization of species complexes on the definition of operational fisheries for Georges Bank provided by Lucey and Fogarty (2014) and delineation of trophic guilds for this region. Garrison and Link (2000) identified trophic guilds of fish and squid based on diet composition data obtained during NEFSC research vessel surveys. Ontogenetic shifts in diet composition were shown to be important for several species; accordingly, we have assigned some species to more than one trophic guild depending on their size. Auster and Link (2009) employed these trophic guilds and examined the question of whether the guilds had remained stable over multi-decadal time scales. Bell et al. (2014) employed dietary guilds to define functional groups using a similar but somewhat consolidated stock complexes. The resulting stock complexes based on our characterization of Fishery Functional Groups is provided in Table 1 for the ten-species prototype analysis.

Table 1. Fishery Functional Groups in Georges Bank Prototype Analysis. Colored Shading indicates species membership in designated functional groups. Light gray shading in the Pelagic Trawl-Planktivore functional group indicates potentially important by-catch species.

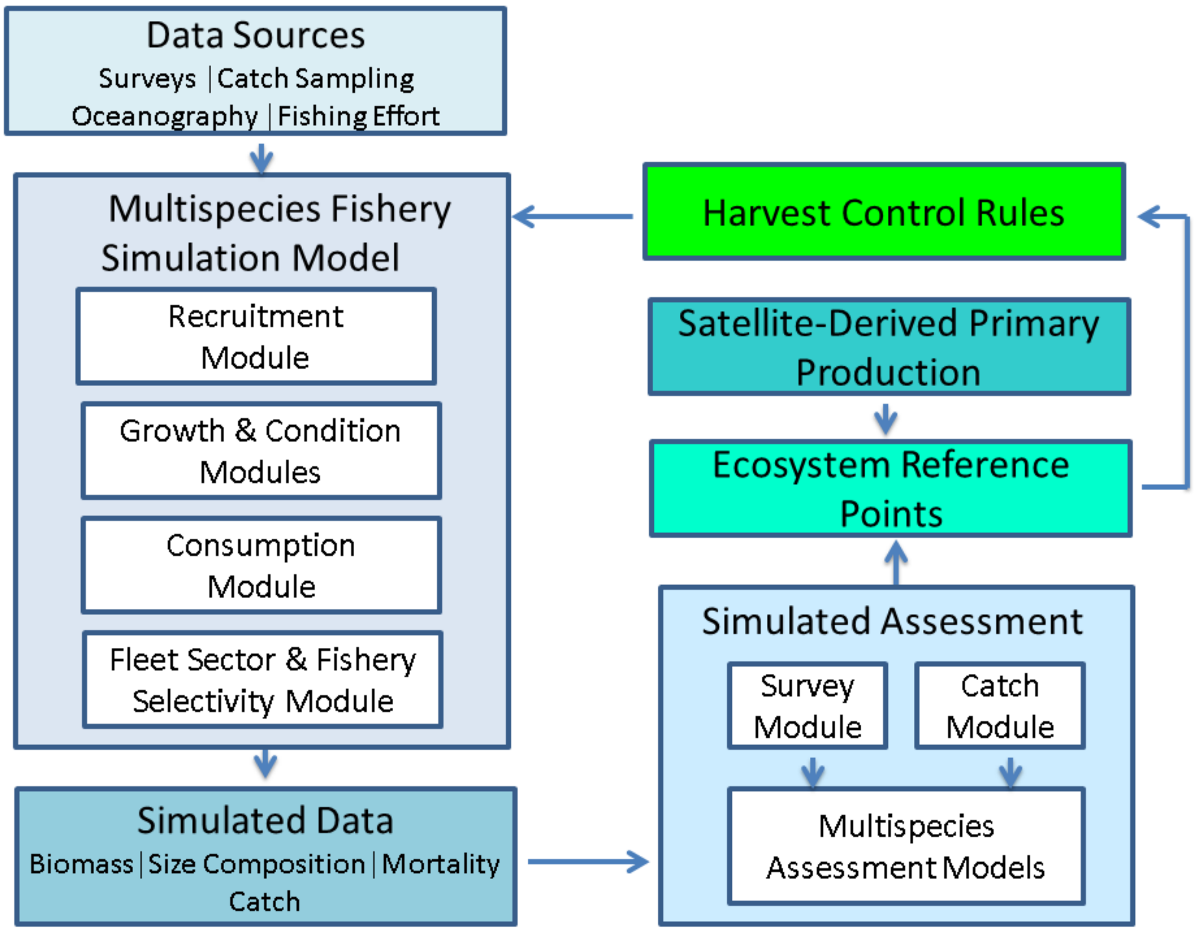
Species		**Fishery Functional Group: Stock Complex**				
Common Name	Scientific Name	**Demersal Trawl-Piscivore**	**Demersal Trawl-Benthivore**	**Fixed Gear Piscivore**	**Fixed Gear Benthivore**	**Pelagic Trawl Planktivore**
Atlantic cod	*Gadus morhua*					
Silver hake	*Merluccius bilinearis*					
Monkfish	*Lophius americanus*					
Spiny dogfish	*Squalus acanthias*					
Winter skate	*Leucoraja ocellata*					
Winter flounder	*Pseudopleuronectes americanus*					
Yellowtail flounder	*Limanda ferruginea*					
Haddock	*Melanogrammus aeglefinus*	Melanogramm				
Atlantic herring	*Clupea harengus*					
Atlantic mackerel	*Scomber scombrus*					

Hydra

Hydra simulates a ten species system 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 (see Appendix 1). We have elected to use a size-based model because fishing processes and predation are size-based rather than age-based and size composition information, in contrast to age composition, is available for most species on Georges Bank. Multiple forms for growth and recruitment are implemented in the operating model to represent different states of nature. In Hydra, the growth function is used to determine the time spent in each length category for each species. Environmental covariates for recruitment, growth, consumption, and for the length-weight relationship can also be included. The latter allows incorporation of change in the condition factor of fish. For simulations presented here, environmental factors including temperature were held constant.

There is no mechanistic feedback between prey consumption and predator growth in Hydra, like most multispecies population dynamics models, including Multispecies Virtual Population Analysis. In the simulations presented here, the implementation of Hydra dictates that sufficient food is always available from the pool of species directly modeled and an 'other' prey category. If evidence supports prey limitation or changes in food quality, it is possible to include prey abundance, availability, and quality in the growth module and the condition module to reflect the changes in predator growth and condition. Figure 1 provides a flow diagram of the process from the multispecies simulations described above to the elements of a simulated assessment process and ultimate specifications of harvest control rules.

Figure 1. Flow chart for simulation testing of proposed management procedure using the Hydra operating model.



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 example, the selectivity curves employed were based on experiments for the species of interest (DeAlteris) and but not all of our 10 prototype species were represented in these experiments. The effort series were patterned on observations for fleet activities on Georges Bank (Mayo et al. 1992; NEFSC 2012) but are not intended to replicate the exact time series of standardized fishing effort on the bank. Accordingly, simulated population levels and yields 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. In these tests, the simulation is run using the 'historical' effort time series for 53 years and then the Management Procedure is implemented and run for an additional 50 years.

Parameterization

The text in this section explains how the Hydra simulation was parametrized for the 10 Georges Bank stocks and how the Hydra simulation model was constructed. While a bit technical, it helps explain that the simulations were based on real estimates of trophic interactions, growth, recruitment, and other factors. Tables and equations referenced below are available from an appendix to examine the specific values used in this example. Some parameters have stochasticity in the values, but in other cases the values may be adjusted to conduct sensitivity analyses.

Parameter inputs to the model for the simulations presented in the main body of the paper are included below. The model is set up to simulate the interactions of 10 species with 5 length bins each and three fishing fleets over the course of 53 years in a single homogeneous area. We summarize parameter sources here and list parameters in Tables S1 (species and length specific parameters), S2 (species-specific parameters), and S3 (predator prey linkages) below.

Length bin widths in cm are specified for each of the 10 species to reflect growth patterns and ontogenetic shifts in feeding across the 5 length bins (Table S1). The model calculates minimum and maximum lengths in each bin based on these bin widths, and converts bin length in cm to weight in g using the standard weight = a times length to the power b. Length-weight parameters (Table S2) for each species were taken from Hall et al. (2006).

Size specific mean stomach weights (equation 14) were taken from Bowman and Michaels, (1984) and aggregated to the model size bins using weighted averages based on sample size in each published size bin (Table S1). While the model allows for annual variation in size-specific stomach weight, we held these values constant for the duration of the simulation.

The initial N at size matrix was taken from (Hall et al., 2006) and summed into model size bins (Table S1)

Growth parameters (Table S2; Figure S1) were estimated by fitting to length at age data from fishery independent surveys of Georges Bank for 8 species with observed data, and taken from Hall et al. (2006) for species lacking length at age data (spiny dogfish and winter skate).

Recruitment parameters (Table S2) were estimated by fitting each recruitment function to age 0 recruits and SSB based on scaled single species stock assessment model outputs for each species (Figure S2). We used stock assessment model outputs to reflect the observed recruitment variability which arises from data on relative year class strength, but attempted to remove stock assessment SSB and recruitment scale which arises from combinations of model parameters which are different than those used here. Scaling was done as follows. Initial models were set up based on average recruitment and deviations, where average age 0 recruitment numbers were scaled until each species achieved a generally stable biomass with species interactions but no fishing mortality. Fishing was then added back in and average recruitment adjusted further if necessary to avoid extinction with fishing. Scaled average recruitment was then used to convert deviations to absolute age 0 recruitment and three SSB based stock recruitment functions were fit to the resulting "recruitment data" using the nls function in R (R Development Core Team, 2015).

Maturity parameters (Table S2) were mainly taken from O'Brien et al. (1993), aside from monkfish which were taken from Richards et al. (2008).

Predator-prey interactions (λ, equation 12) were governed by a vulnerability matrix (Table S3) where the possibility of one species eating another was determined by review of food habits data (Link and Almeida, 2000; Smith and Link, 2010).

Fishery selectivity parameters (Figure S3) were derived from De Alteris and Grogan, (1997). The parameters reported there were converted to ours as follows: DeAlteris and Grogan's alpha2 (curve steepness) is equal to our d in Equation 16. DeAlteris and Grogan's Selection Factor (SF) is the length at 50% selection (L50) divided by the average mesh or hook size, and our c in Equation 16 is -alpha2*L50, so we used c = -d * SF * average mesh or hook size. We used average values for diamond mesh trawl (gear 1) and offshore trap (gear 2) because they existed for all species studied, which were Atlantic cod, haddock, yellowtail flounder and winter flounder. We further assumed that the trawl fleet would catch all species, that the longline fleet would catch Atlantic cod, haddock, dogfish, skates, and goosefish, and that the pelagic gear would catch Atlantic herring, mackerel, and haddock as shown in Figure S3.

The bottom water temperature time series for Georges Bank used to parameterize annual temperature in equation 14 was taken from the Northeast Fisheries Science Center Ecosystem Status Report (NEFSC, 2012), and is illustrated in Figure S4. The time series spans 1977 to 2010; we used the 1977 temperature for our first 15 model years, the 1978-2010 temperatures for the next 34 model years, and repeated the 2010 temperature for the final 4 model years. (This temperature time series can now be updated with observations to 2015, which will be used for future analyses. We note that our model run did not include the record high 2012 temperature in the current time series.)

Several model parameters were held constant for simplicity in these simulations. Mortality due to all unmodeled factors (M1, equations 11 and 20 above) was set constant for all length bins, years, and species at 0.10. The preferred predator/prey weight ratio on a logarithmic scale (Ψj in equation 13 above) was set at 0.5 for all species, and the variance in predator size preference (σj2 in equation 13 above) was set at 2.0 for all species, as recommended in Rochet et al. (2011). The food intake parameters (equation 14) were set to дi = 0.002 for dogfish and skates and 0.004 for all other species, and жi = 0.11 for all species following recommendations in NEFSC 2010, Appendix B (http://www.nefsc.noaa.gov/publications/crd/crd1003/pdfs/butterapp1.pdf). Other prey biomass (Ω in equation 15) was set to 30,000. The number used in Hall et al. 2006 was not reported, but was tuned until stable dynamics and "sensible" M2 levels were achieved; we similarly tuned this parameter to be the smallest number that stabilized dynamics of prey species (herring, mackerel, and silver hake) in the no fishing runs.

Simulated Stock assessment

From the simulated series of biomass, length composition, survival rates, and catch generated by Hydra we generated 'observational' data incorporating environmental stochasticity and measurement error. We simulated the survey process by taking the population outputs from Hydra and applied survey catchability coefficients and area swept corrections for each species and added variability to reflect factors such as measurement error and variation in availability to the trawls at the time of sampling. We then used the generated survey data both as inputs to stock assessment models and as model-free estimators to be used to test the performance of model-free biomass estimates.

The assessment models used included a 10-species multispecies production model of the Lotka-Volterra type and a multispecies delay-difference model that took into account simple demographic structure (prerecruits and post-recruits). In the latter, predation mortality was assumed to be concentrated during the pre-recruit phase of the life history, consistent with observations for Georges Bank and other marine ecosystems.

Reference Points

The proposed management procedure entail defining an ecosystem overfishing definition to be applied at the system and stock complex levels based on energetic principles. Any definition of optimum yield at an ecosystem level should be based on the energy coming in at the base of the food web to fuel production. Specifically, we propose to use the ratio of Microplankton Production to Total Primary Production as a limit reference point. The proposed ratio is intended to reflect the importance of production that is replenished each year by new nitrogen reaching the euphotic zone with the breakdown of stratification and increased mixing in winter and spring. In a sense, this fraction of the total primary production represents growth potential expressed as a fraction of total production. Further, it bounds the harvesting problem by explicitly recognizing that there are clear constraints on overall fishery production. In an ecosystem subject to mass-balance constraints, this growth potential would be altered by top-down controls and other factors and would be utilized throughout the system with harvest removal just one element.

The proposed limit reference point can be defined objectively using satellite-derived information and it can be updated continuously. The estimated mean ratio of microplankton production to total primary production over the last 25 years from satellites has been relatively constant at around 0.27. Any attempt to take this fraction of the total production would clearly by unsustainable from an ecosystem perspective – it would leave no energy for replenishment of the upper trophic levels. To avoid this problem, we propose lower target exploitation rates ranging from 2/3 to 1/2 of the limit reference point. For the purposes of the simulations reported here, we have rounded the limiting exploitation rate to 0.3 and have explored target exploitation rates of 0.15-0.20. To place this in context, current levels of F_{msy} or their proxies (where available) for the species included in this analysis range from 0.17 to 0.54 based on single-species stock assessments.

We next need to define the safety nets to be used for the species comprising the Fishery Functional Groups. Because the specification of overfished levels in single-species management is framed in terms of biomass levels relative to B_{msy}, we will follow convention in specifying the species floors in terms of biomass. We propose several variants on this theme. First, an overall baseline for remedial action is established when the biomass of any species falls below 20% of its unfished biomass. We also consider setting higher thresholds for species with vulnerable life history characteristics, especially the elasmobranchs which have delayed maturation relative to telesosts and much lower fecundity levels. In the simulations presented here we set the floor at 30% of unexploited biomass for elasmobranchs (although higher thresholds can of course also be explored). We also consider the situation where the baseline level is set for the species complex as a whole. This option is of course less conservative and entails higher risk to individual species. Here our focus is on documenting the increase in risk entailed in using this strategy.

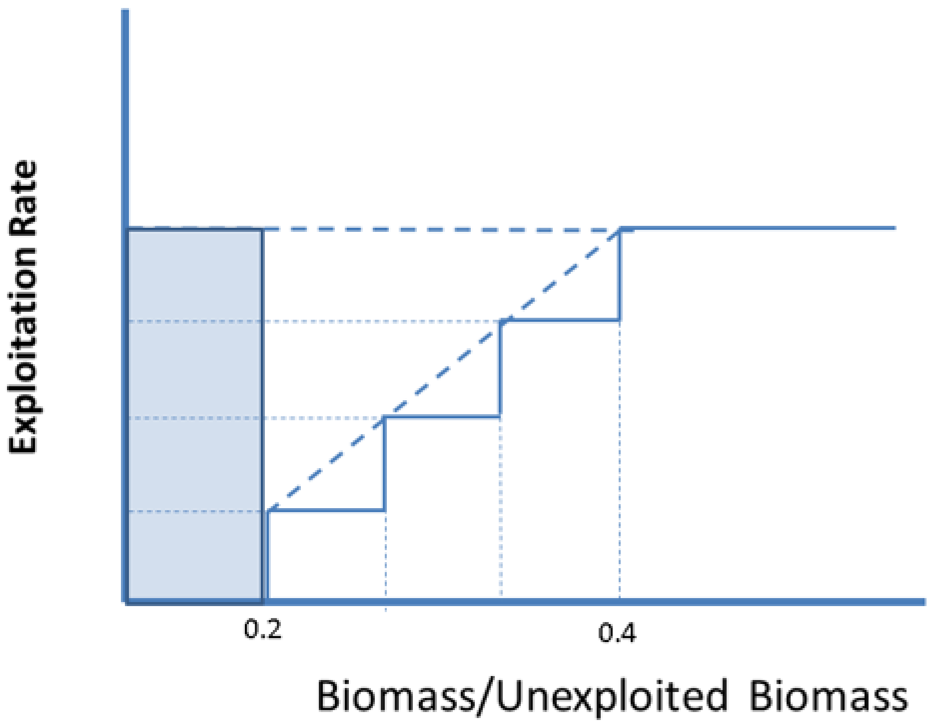
Harvest Control Rules

We explored six principal scenarios with three variations within each (Table 2) to define options for harvest control rules but here we will present information on a subset of outcomes. The harvest control rules involve different options for floors and ceilings. Three ceiling levels are defined at the system level based on exploitation rates of 0.3, 0.2, and 0.15. In the present set of simulations, we have translated these exploitation rates directly in application to the species complex level with each subject to this same sequence of exploitation levels. We translate these exploitation rates into standardized fishing effort by dividing by the mean catchability coefficient for the species in the complex. It should be noted that these exploitation rates defined at the species complex level will be manifest as different rates on the individual species level because of different gear selectivity factors. The resulting catch for the complex as a whole and the individual species catch within each species complex is determined by the product of these species-level partial recruitment factors and the total biomass of the species complex. The exploitation rates specified above should be considered as fully recruited exploitation rates for the complex as a whole.

Table 2. Example scenarios

Scenario 1:	**Constant exploitation (no ramp down) at Ex=0.3; 0.2; 0.15 and Floor=0.2 applied at the stock complex level**
Scenario 2:	**Constant exploitation (no ramp down) at Ex=0.3; 0.2; 0.15 and Floor=0.2 applied at the individual species level**
Scenario 3:	**Constant exploitation (no ramp down) at Ex=0.3; 0.2; 0.15 and Floor=0.2 for each species except skates and dogfish (Floor=0.3)**
Scenario 4:	**Ramp-down exploitation using 'steps' at Ex=0.3; 0.2; 0.15 and Starting at B/Bo = 0.4 applied at the stock complex level**
Scenario 5:	**Ramp-down exploitation using 'steps' at Ex=0.3; 0.2; 0.15 and Starting at B/Bo = 0.4 applied at the individual species level**
Scenario 6:	**Ramp-down exploitation using 'steps' at Ex=0.3; 0.2; 0.15 and Starting at B/Bo = 0.5 applied at the individual species level for skates and dogfish**

Figure 2. General form of control rules considered in this example management strategy evaluation including constant exploitation rate over all biomass levels and graduated (or ramped) exploitation rate with declining exploitation initiated when the ratio of current biomass to unexploited biomass reaches a specified minimum threshold at (a) the (Stock complex level or (b) the individual species level. The simulations employ three Maximum Exploitation rates set at the limit exploitation rate (0.3) and choices of two target exploitation rates (0.2 and 0.15). A total of 18 different scenarios were run using different combinations of these factors.



Performance metrics

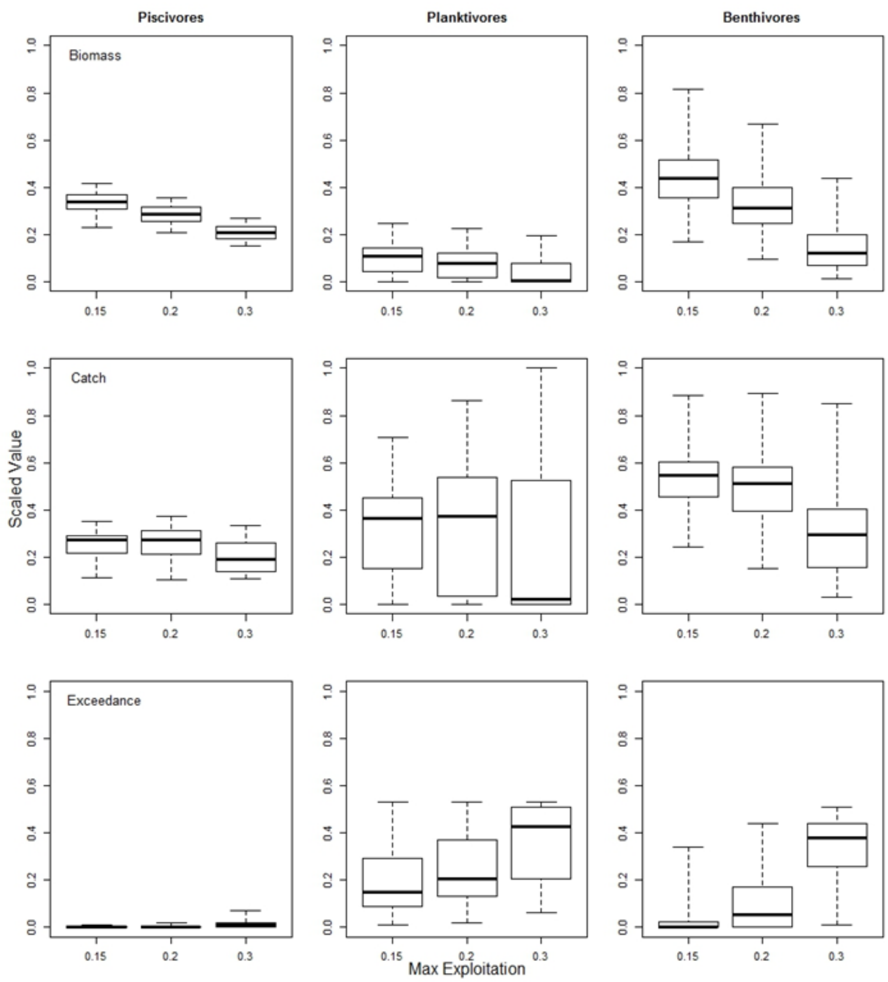
To evaluate fishery performance, we examine Catch, Biomass, and the fraction of simulation runs in which the stock complex constraint (floors) was exceeded. We used the median result of the 500-member ensemble to compare different control rules and their variants but show the full range of results characterizing uncertainty with a focus on the interquartile range. In the simulations, we also output the associated revenues, the size composition of the catch and the population for each species. Additional metrics including measures of biodiversity are also part of the output. For the purposes of this demonstration, we will focus on catch, biomass, and the frequency of exceedance of the overfished definition.

Results

In the following section, will provide a description of a small subset of the results from the 18 scenarios investigated to provide a flavor of the types of outcomes observed to date. Because of substantial differences in the biomass and catch of component species and fishery stock complexes included here, we have scaled the results to allow ready comparison across the different scenarios. The results are scaled by dividing by the largest value of median biomass and median catch. Because the figures for the frequency of exceeding the protective floor levels, no rescaling was necessary. We have provided results at the stock complex and individual species levels in a way that integrates the results over fleet sectors.

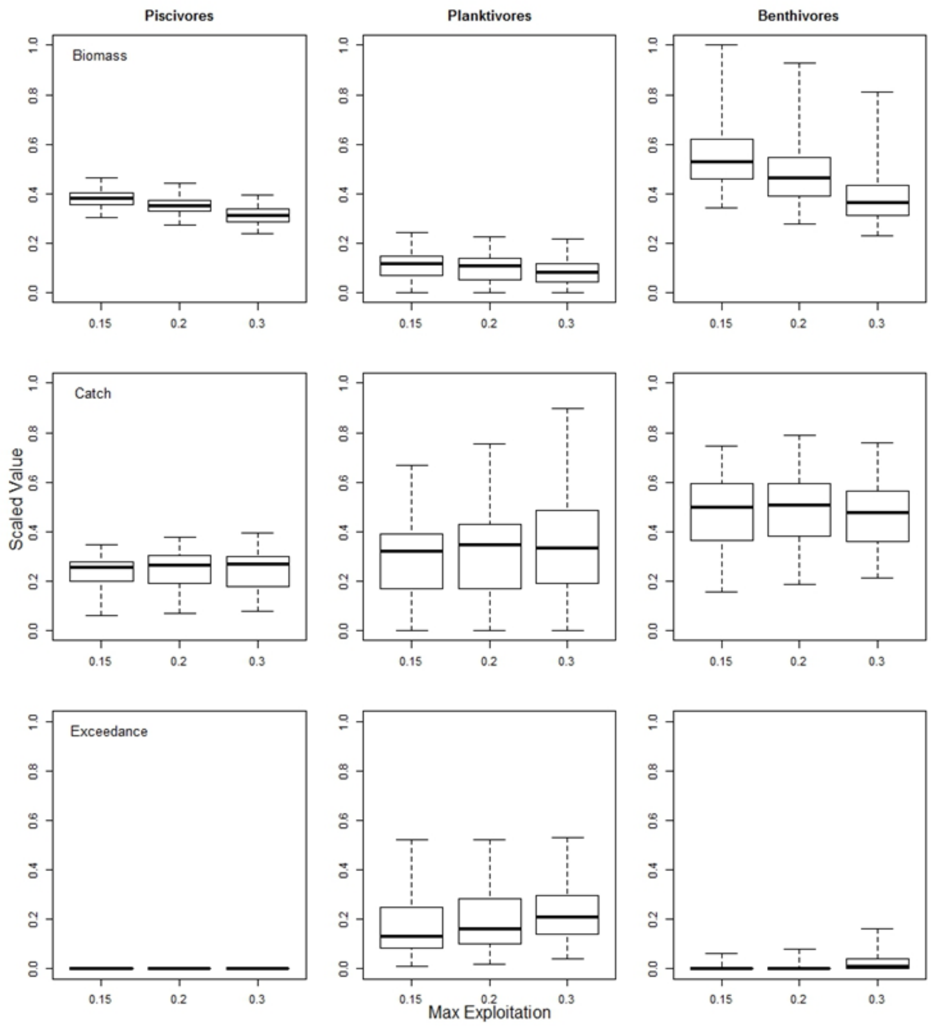
Figure 3 presents comparisons of scaled median catch and biomass among the stock complexes for the constant exploitation rate strategy; in this example, the threshold exceedance level was triggered when stock complex biomass as a whole fell below 0.2. As expected, the biomass declines with increasing exploitation rate in each stock complex. In contrast, the median catch remains roughly comparable among stock complexes at the lower exploitation rates of 0.15 and 0.2 but is less with an exploitation rate of 0.3 and exhibits increased variability in outcomes. When the threshold exceedance level is set for the stock complex instead of for individual species, high frequency of exceedance levels occurs for the planktivore and the benthivore stock complex, particularly when the maximum exploitation rate is set at the limiting level of 0.3.

Figure 3. Comparison of scaled biomass (upper row), catch (middle row) and exceedance levels (lower row) by stock complex integrated over all fleet sectors for the constant exploitation rate control rule.



When we apply a graduated control rule in which reductions in exploitation rate from the maximum are initiated when the stock complex as whole drops below the ratio biomass to unexploited biomass, we see increases in relative biomass and catch relative to the constant exploitation strategy and sharp reductions in the frequency of exceedance of the protective floors, although the exceedance levels of planktivores remain higher than is desirable (Figure 4).

Figure 4. Comparison of scaled biomass (upper row), catch (middle row) and exceedance levels (lower row) by stock complex integrated over all fleet sectors for the graduated exploitation rate control rule.



In Figure 5 and Figure 6, we compare the performance of the constant exploitation rate strategy with the graduated response control rule when the protective floor is invoked when any individual species within a stock complex falls below a threshold biomass level of 0.2 of the unexploited biomass. In this case, we show the exceedance levels for individual species. Again, the application of the graduated response considerably, and not unexpectedly, results in reduced frequency of exceedance of the threshold floor level.

Figure 5. Comparison exceedance levels by species integrated over all fleet sectors for the constant exploitation rate control rule and the protective floor implemented at the species level.

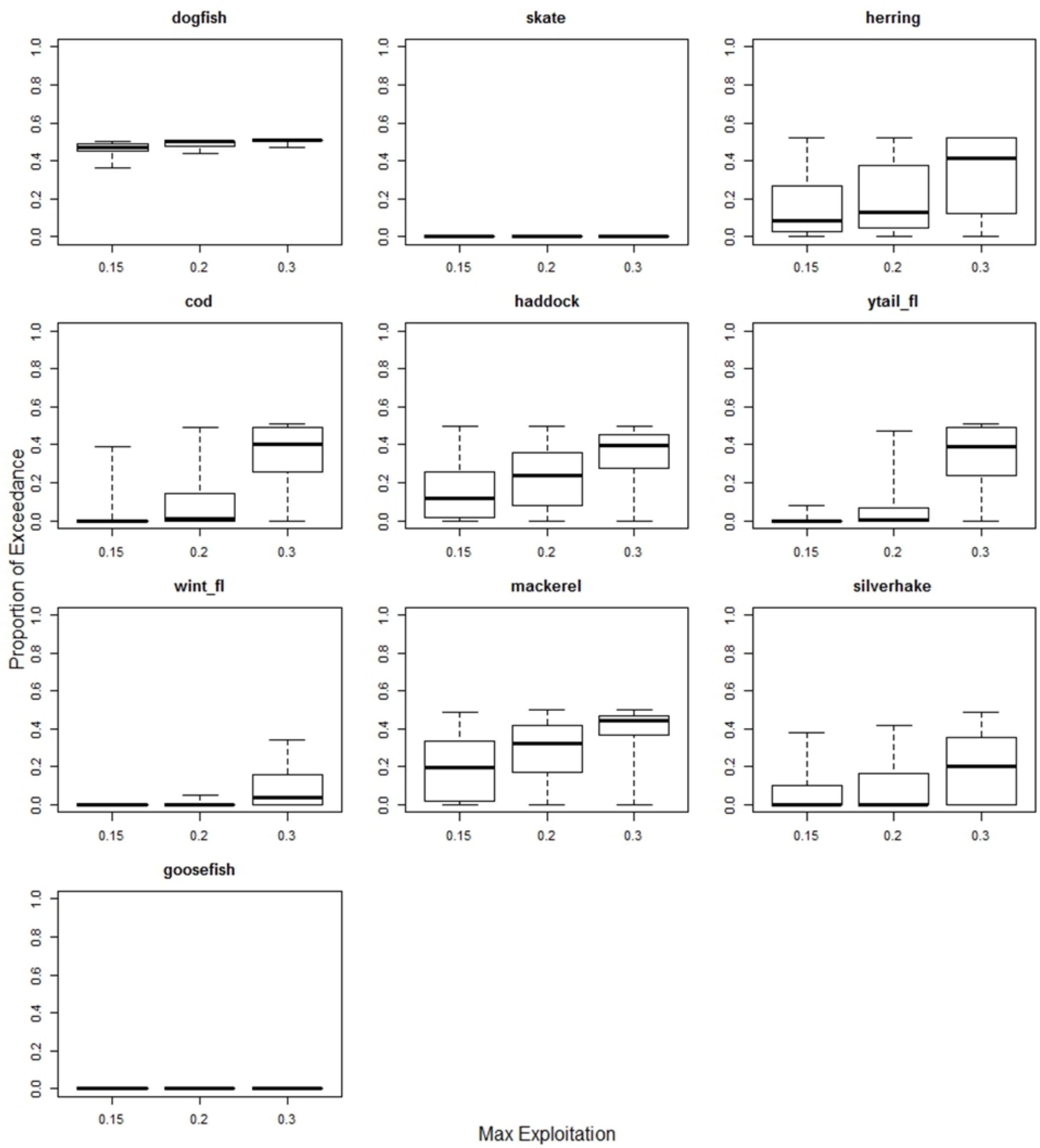
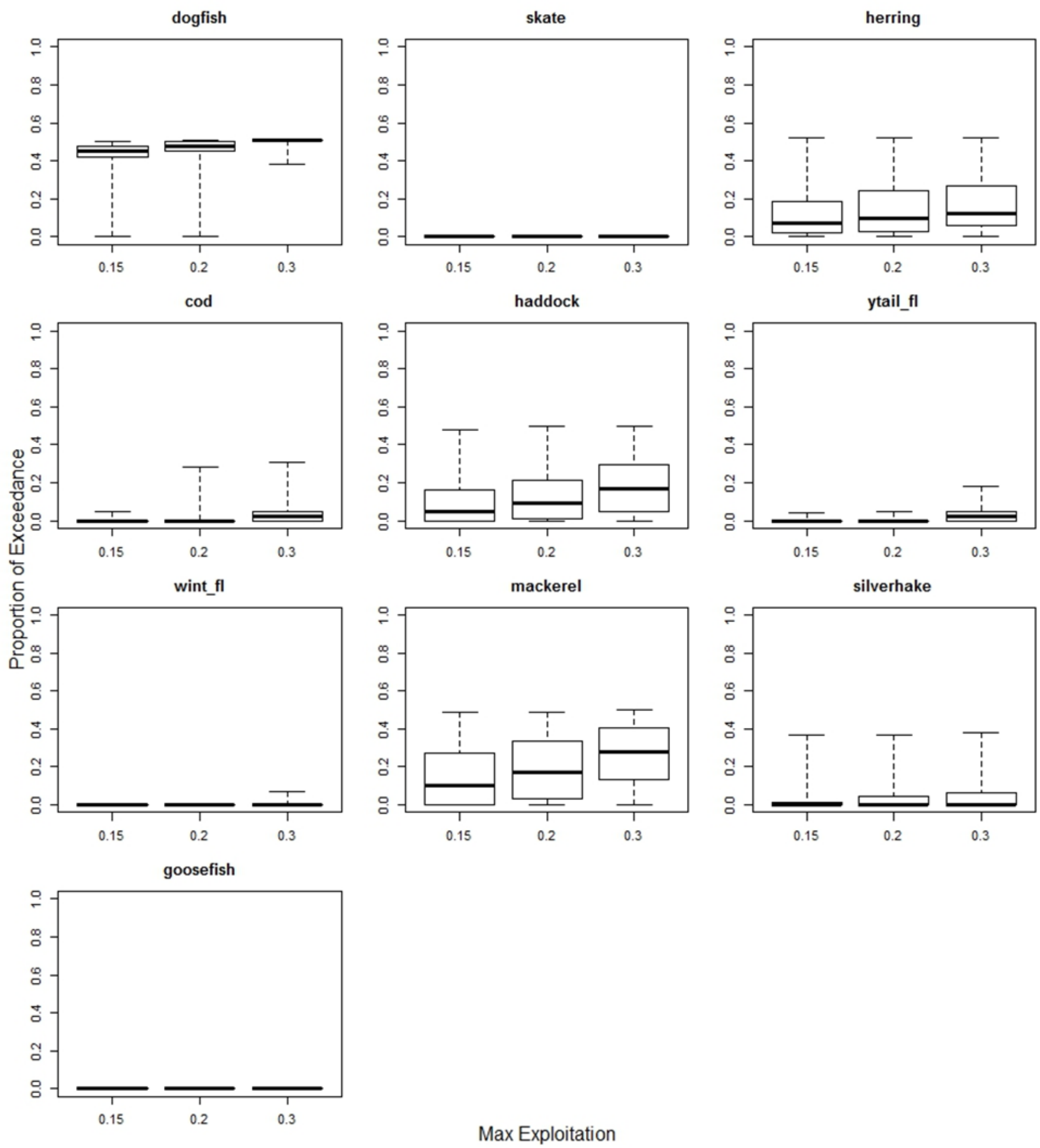


Figure 6. Comparison exceedance levels by species integrated over all fleet sectors for the graduated exploitation rate control rule and the protective floor implemented at the species level.



Collectively, these results show that under all scenarios chosen for illustration, the limit exploitation rate of 0.3 is often too high to allow acceptable performance with respect to the protective constraints tested here while also resulting in poorer catch performance. Application of the graduated exploitation response results in overall improved performance with respect to the threshold exceedance levels with little or no loss in yield at the stock complex level.

Kraken-Portfolio Analysis

The NEFMC recently identified stability as a core component of its risk policy. In its Risk Policy Roadmap, stability is defined as "*Evaluating the trade-offs of minimizing variability while achieving the greatest overall net benefits to the nation*", and that "*Metrics that monitor variability from year to year, e.g. in quotas, should be developed*" (Risk Policy Working Group 2016). The overarching goal, then, is to assess the trade-offs between generating a high flow of benefits and the ability to ensure that flow of benefits can be generated in a stable and sustainable manner.

In economics, modern portfolio theory was developed to assess this exact trade-off (Markowitz 1952). Portfolio analysis measures the extent to which financial assets change relative to each other, with the idea that in a well-balanced portfolio a decrease in the value of one asset will be off-set by an increase in another. The framework has been extended to assess trade-offs in fishery management (Edwards et al. 2004, Sanchirico et al. 2008), in that species and guilds can be viewed as generating a flow of benefits whose stability can be assessed in a similar manner to financial assets.

Jin et al. (2016) employed portfolio theory to assess historical performance in the Northeast Large Marine Ecosystem, in terms of minimizing the variance around the attainment of a revenue target. In an extension, this model can be coupled to the multispecies models such as Hydra and Kraken to provide measures of stability and returns for the Georges Bank within a simulated world. As a worked example, of this approach, we have coupled the portfolio analysis with the Kraken surplus production function. We develop species-level floors (minimum biomass levels), defined here as 20% of unfished biomass, from Kraken. Guild-level ceilings (maximum removals for each guild modeled) are defined as 18% of the summed Guild-level biomass. In each time step, the choice of optimal harvest strategies, based on the historical time series of revenue and biomass generated from Kraken and in terms of a balanced portfolio, can then be passed back to the operational model to generate a simulated harvest trajectory. The biomass is then updated to reflect the simulated catch and the process can be iterated for the requisite number of time steps.

Figure 7 to Figure 9 presents the simulated historical versus optimized revenue as a percentage of each simulation's mean value to facilitate comparison across species. It is particularly important to keep in mind that the revenue target is constant across the portfolio-optimized component of the simulation, which is an assumption which can and should be revisited when ultimately engaged in assessing management alternatives. The results of the simulations indicate that the optimal portfolio is chosen to direct catch away from species with either substantial historic volatility, high positive correlations with other species in the system, or a mix of both.

For example, in a balanced portfolio, optimal revenue of both Species 3 and 9 (Figure 7) are substantially lower than historical levels. Conversely, species such as 1 and 6 (Figure 7) are exploited more heavily by the model, given their substantially lower historical variability. Comparing revenue to catch (Figure 7 vs. Figure 8), there is general concurrence in regards to the direction of the shift across species. However, there are some distributional differences worth pointing out. For example, comparing revenue vs. catch for Species 8, the revenue variability of the optimized simulation results is substantially higher than the catch from the same period. The opposite can be said for a comparison of the historical revenue versus catch for Species 8.

Figure 7. Historical species revenue versus portfolio optimized **revenue**.

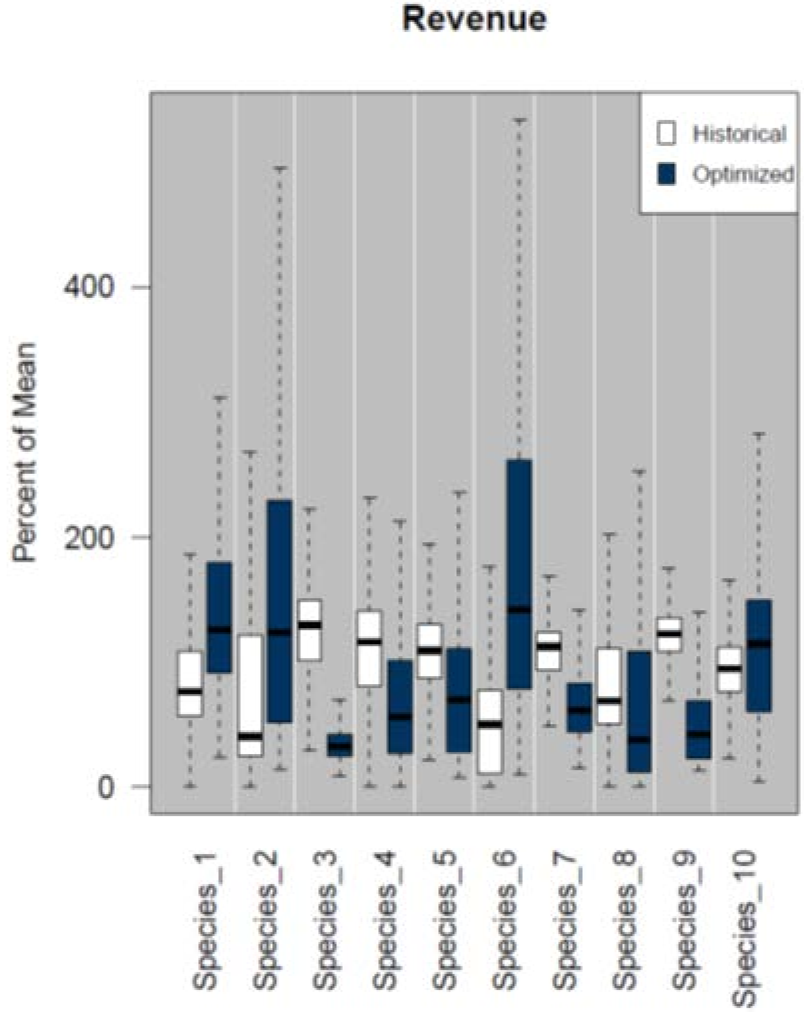


Figure 8. Historical species catch versus portfolio optimized **catch**.

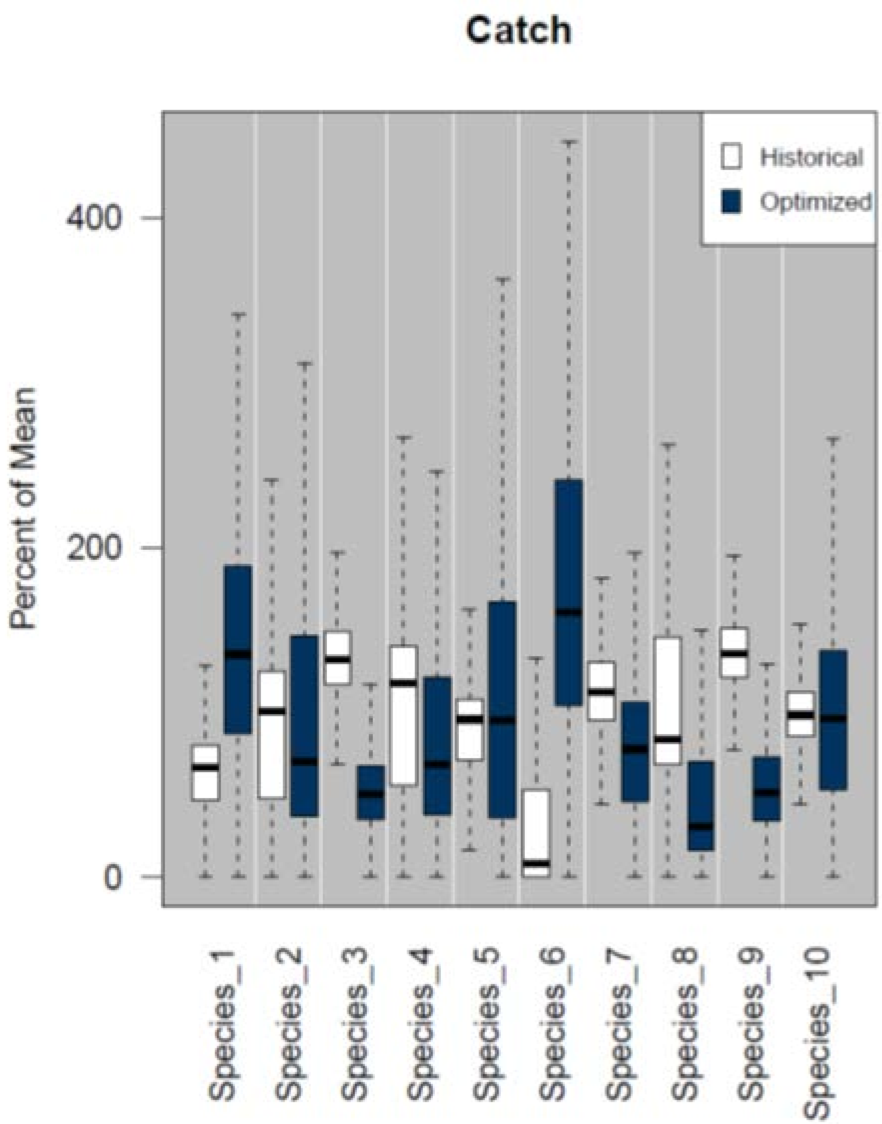
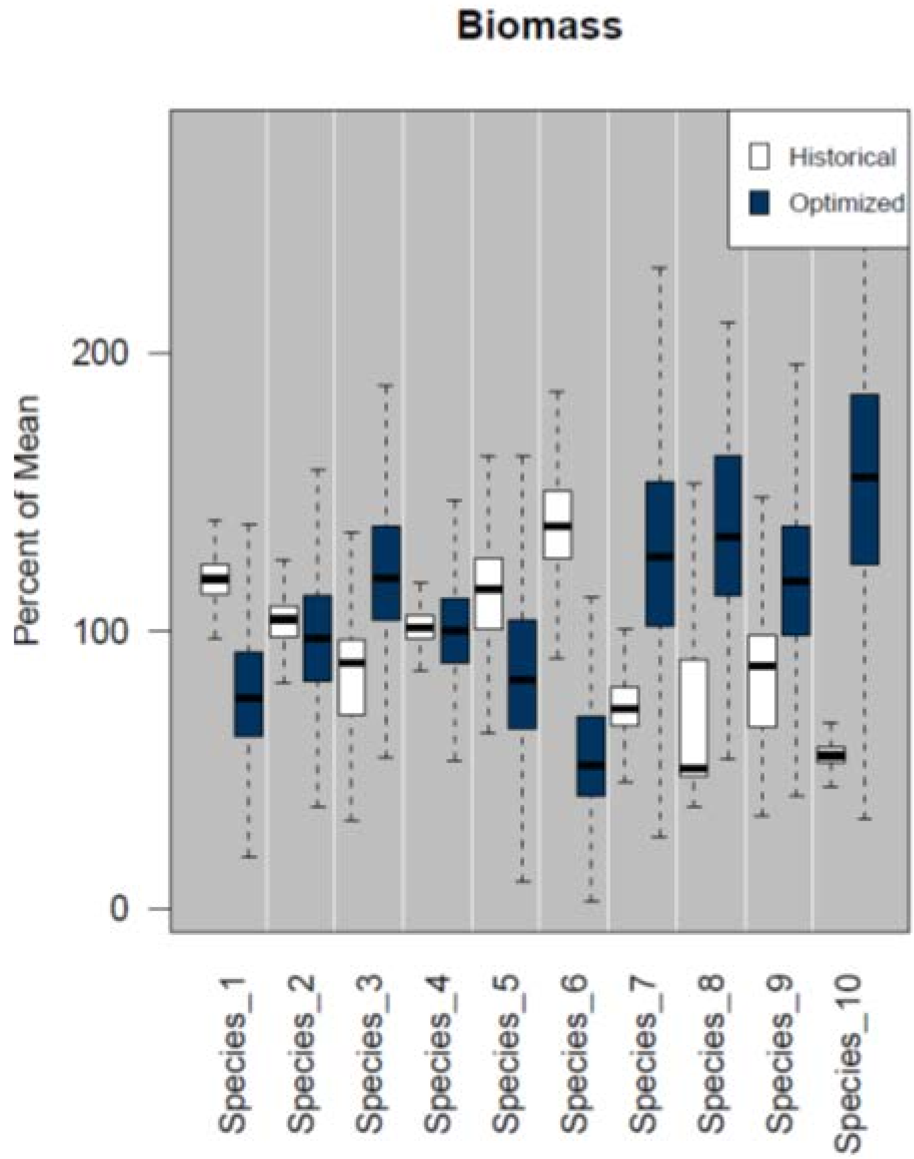


Figure 9. Historical species biomass versus portfolio optimized biomass.



This suggests that the portfolio is exploiting differences between biological and market correlations in minimizing the variance surrounding system-level revenue. Additionally, the optimized revenue for Species 8 indicates substantial increases in variability when compared to the historical revenue flow. This highlights an important consideration, in that although the optimal portfolio species mix minimizes the variance in the system at large, any single species could actually be associated with increased variability in revenue and catch streams. A similar result can be seen in the biomass of Species 1, which exhibits a substantial increase in variability within the optimized segment of the simulation when compared to the historical segment.

Figure 10 and Figure 11 present histograms of the number of times across simulations either the guild ceilings or species floors bind. A comparison of the two figures indicates that the species floors bind much more frequently than the guild ceilings, which indicates that the optimum portfolio is more sensitive to the exploitable biomass within, rather than between, guilds.

Figure 10. Number of binding Guild ceiling constraints across simulations.

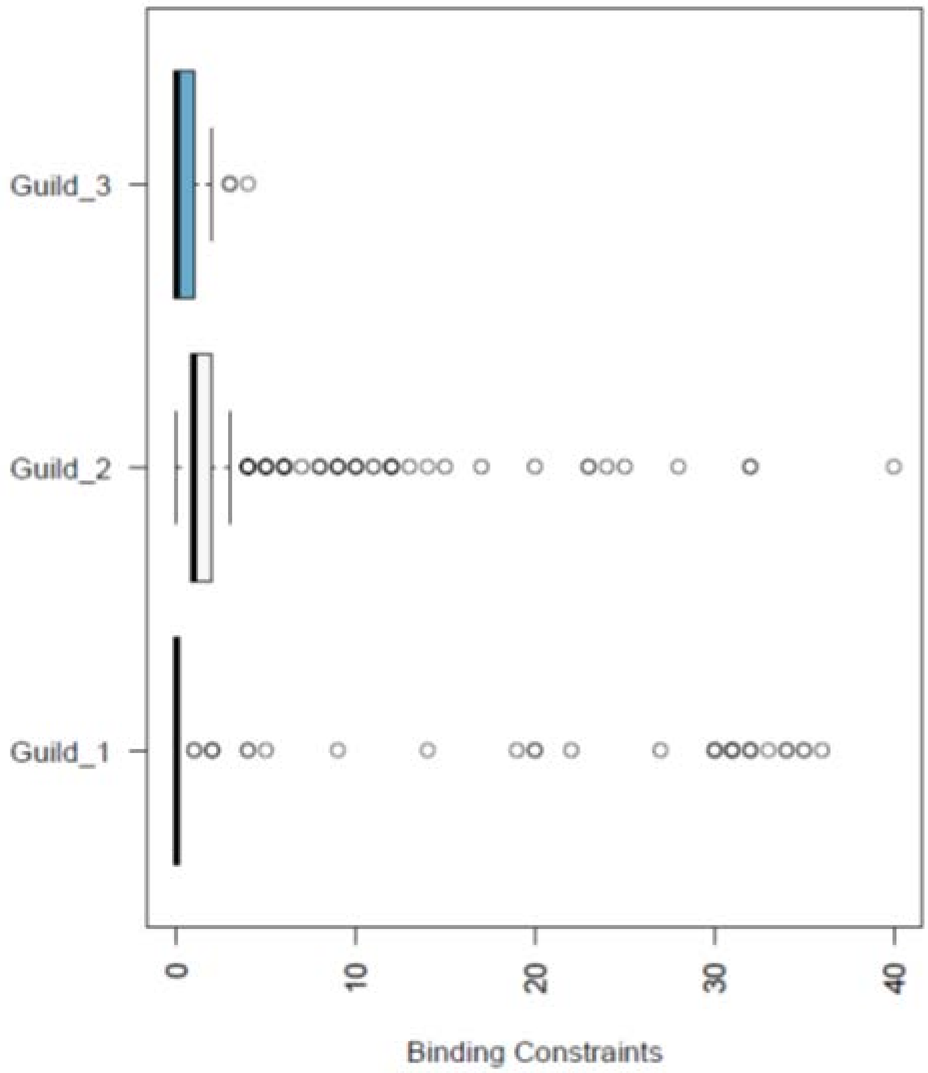
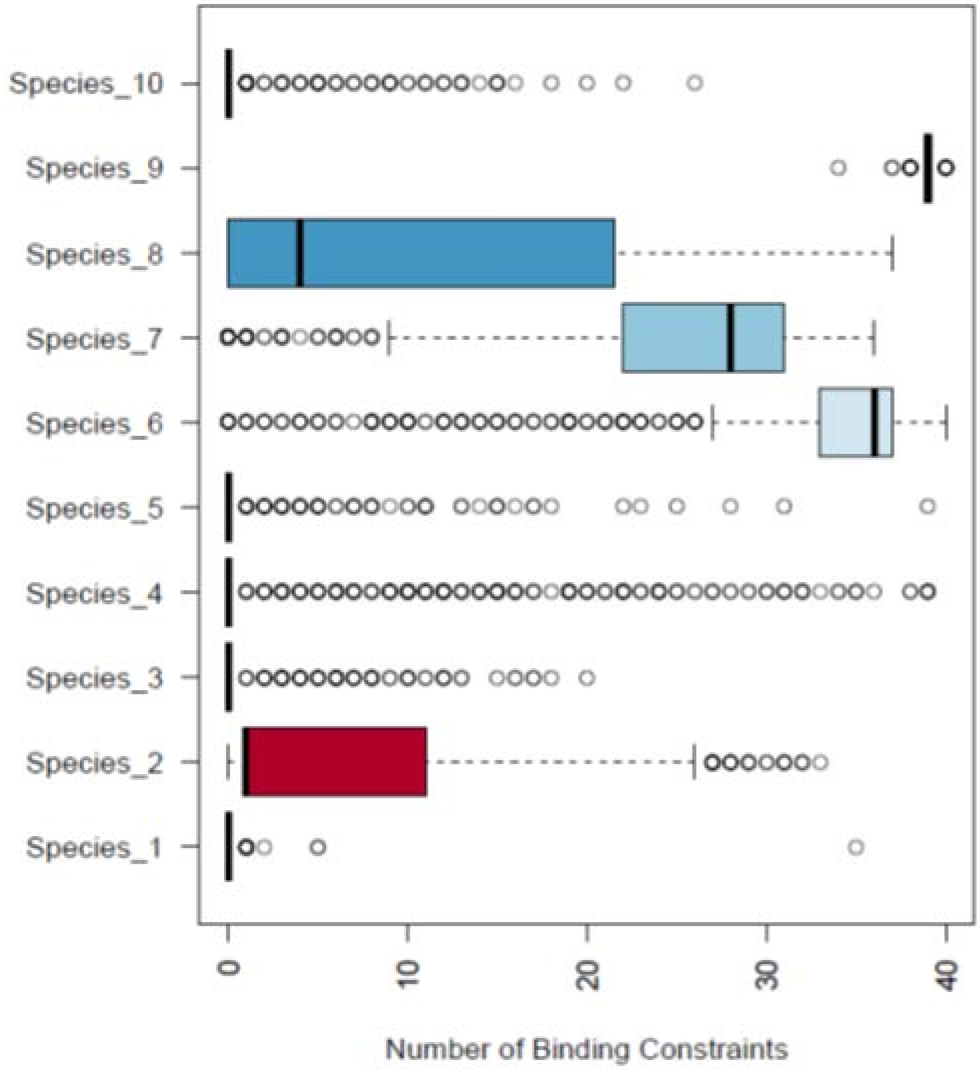


Figure 11. Numbers of binding species floor constraints across simulations



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