USING PORTFOLIO THEORY TO IMPROVE THE MANAGEMENT OF LIVING MARINE RESOURCES:

A DEMONSTRATION FOR NEW ENGLAND FISHERIES

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Abstract

Management of multispecies fisheries can take advantage of interactions among species. A more diverse portfolio of species has more asynchronous trends in productivity that can help to maximize multispecies yield. We are investigating the feasibility of implementing a portfolio approach to fisheries management, and this report demonstrates a worked example for fisheries managed by the New England Fishery Management Council to show that these estimates are feasible with publicly available data. There was a declining trend in landings from this portfolio through the 1950–2021 time series but an increase in revenue, driven mostly by sea scallops. Correlation in revenue was generally positive among species managed under the Northeast Multispecies Fishery Management Plan, but landings of other species managed by NEFMC were negatively correlated with groundfish to diversify the portfolio. Economic frontier analysis of the example portfolio indicated that the same amount of revenue could have been achieved with less risk of foregone yield, or more revenue could have been obtained for the same risk. This example demonstrates that there are benefits to coordinated fishery management in terms of decreased risk of foregone revenue.

Introduction

Traditional approaches to fisheries management have inherent uncertainties that undermine social, economic and ecological outcomes, which will only get worse as the climate continues to change (c.f. Link 2010, 2018). Fisheries management often focuses on single species or populations. For example, in classical fisheries management, management is based on individual stock dynamics with limited or no consideration of the entire fishery system (Browman and Stergiou 2004). Although this approach has resulted in many positive outcomes (Hilborn et al. 2015, Lynch et al. 2018), it largely ignores multispecies interactions and economic risks (Link 2010, 2018).

For most US fisheries, management is focused on a single species or stock level and does not consider environmental or ecological linkages (Skern-Mauritzen et al. 2016, Marshall et al. 2019). There are some exceptions, mainly in the Pacific, North Pacific, West Pacific, and South Atlantic regions (Link and Marshak 2019), with some considerations of aggregate biomass or group-level catch caps, limits or combined management. In the US federally managed species fisheries information system, only 8% have some form of ecosystem consideration included in their assessment or management advice (Lynch et al. 2018).

Fishery managers are tasked with making many decisions, including annual catch limits, fishing effort and fishing behavior. These decisions benefit from a coordinated approach to all species and fisheries in an ecosystem. There is growing evidence that traditional approaches to fishery management can yield suboptimal outcomes, especially as environments continue to change (Fogarty 2014, Lynch et al. 2018). There is also evidence that single-species approaches can result in considerable foregone yield (Fogarty 2014, Link 2018). An ecosystem approach to fishery management is advisable to meet the variety of statutory requirements (Murawski 1991, Link 2010).

There are important risks to consider for meeting fishery objectives (e.g., overfishing, fishery efficiency, market shifts, catchability, climate change impacts, etc.). To mitigate the risks of foregone revenue, portfolio approaches and theory have been explored in the context of marine fisheries (e.g., Edwards et al. 2004, Sanchirico et al. 2008, Rădulescu et al. 2010, Schindler et al. 2015, Jin et al. 2016, Carmona et al. 2020). This approach represents a systemic treatment of all stocks or fisheries in an ecosystem and focuses on the aggregate dynamics of a group of species. As with a financial stock portfolio (Markowitz 1952, Roy 1952), the emergent properties of a diverse portfolio of management units will be more stable than any one unit on its own (Doak et al. 1998, Sanchirico et al. 2008, Brown et al. 2018, Link 2018). When examined theoretically, empirically, experimentally, or via simulations, portfolio management consistently produces better outcomes, including increasing revenue from the resource and reducing risk of foregone yield (Edwards et al. 2004, Link 2018). Theoretical studies demonstrate that the further away from the "efficiency frontier" that a set of aggregated landings is, the more risk is incurred and the less economic yield is obtained (Figure 1; Rădulescu et al. 2010, Jin et al. 2016, Carmona et al. 2020). Multispecies approaches to management can also benefit stock status and regulatory stability within current legal mandates. Furthermore, a multispecies portfolio approach has the flexibility to mitigate unforeseen challenges or new pressures (Schindler et al. 2015, Link 2018).

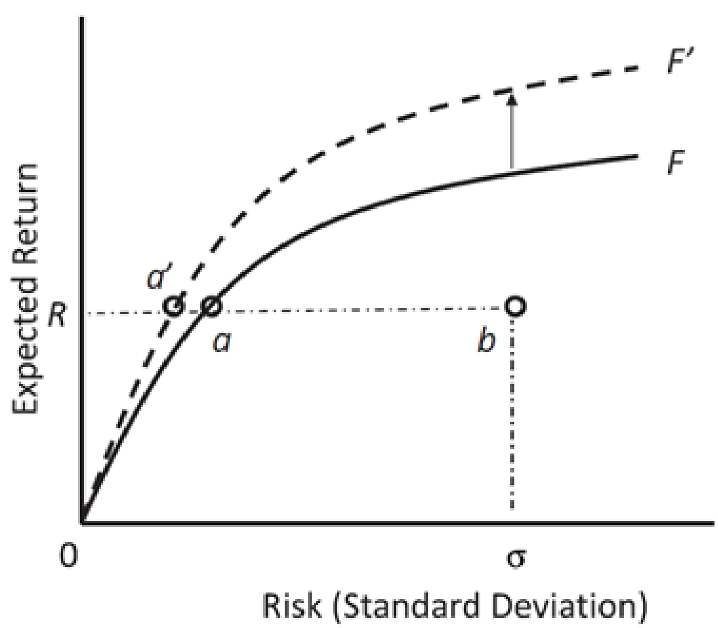

Figure 1. The efficient frontier and the risk gap in which R represents a given level of total revenue; F and F' are two efficient frontiers single species and ecosystem-based fisheries management); b denotes the actual portfolio; a and a' denote the optimal portfolios on F and F'. The distance between b and a or a' represents the risk gap (from Jin et al. 2016).

Based on these findings, fishery managers may be able to mitigate risks and achieve better outcomes by more coordinated management of multiple species. Within a larger project to investigate the feasibility of implementing a portfolio approach to fisheries management in the United States, this report demonstrates a worked example for New England fisheries to show that portfolio analyses are feasible with the available data and can be considered for fishery management. The demonstrated example can be modified and extended with feedback from the New England Fishery Management Council (NEFMC) and its Scientific and Statistical Committee.

Methods

Data Selection and Processing

The data used are from the publicly available NMFS Landings database (https://foss.nmfs.noaa.gov/apexfoss/f?p=215:200::::::). These data provide coverage across geography, taxonomy, and fishing sector, reporting on value, amount, and related information. The full time series (1950–2021) for all species was downloaded by year, state and species with New England selected for the region. Landings information by state for the region was included as this could allow for examination of specific states in the future if required. Data exploration and frontier analysis was conducted using R (v4.2.2).

The dataset required extensive data cleaning prior to analyses. We focused on commercial landings, removing all rows marked "confidential" with no landings and revenue data. We considered five potential solutions for each species with missing data: exclude the taxa from the analysis, aggregate taxa, truncate the time series, interpolate, or add 'true zeros' for missing landings. Revenue was adjusted for inflation, using World Bank inflation data to 2021 (Condylios 2022). We focused on landings in metric tons rather than pounds to avoid zero records. Species selection for the candidate portfolio is a prerequisite to frontier analysis. Here we limited the portfolio to species managed by the New England Fisheries Management Council (NEFMC).

Frontier Analyses

We used the value-at-risk methodology from the J.P. Morgan RiskMetrics VaR model (J.P. Morgan/Reuters, 1996) to evaluate minimization of risk (standard deviation) for desired levels of revenues for portfolios of regional fisheries stocks. By minimizing risk over a range of potential revenues, we created efficient frontiers to illustrate minimal level of risk achievable for a desired revenue level given the historical performance of fisheries stock portfolios. We calculated two efficient frontiers: a portfolio frontier representing ecosystem-based fisheries management and a species frontier which is analogous to single-species management approach. Efficient frontier curves were generated in R (version 4.2.0) following the methods used in Jin *et al.* 2016, based on Sanchirico *et al.* 2008. The curves were calculated by using a quadratic optimization algorithm (ipop, R kernlab package – Karatzoglou et al 2022; based on the LOQO software Vanderbei 1999) to solve Eqn. 1, whereby optimal revenue weights are determined for each species that minimize the risk associated with attaining various target revenues, while accounting for biological constraints.

$$min_{\mathbf{w_t}} \mathbf{w}_t{}' \textstyle\sum_{\mathbf{t}} \mathbf{w_t} \;\; s.t. \, \mathbf{w}_t{}' \boldsymbol{\mu}_t \geq R_t, w_{i,t} \;\leq\; W_{i,t} \; \forall i \qquad \text{Eqn. 1}$$

Note: bold typeface indicates a vector or matrix

i = 1,….,n is the species index

$\boldsymbol{w_t}$= vector of revenue weights calculated at time *t.* Revenue weights allow managers to select the harvest level for each species in the portfolio to minimize risk

$\sum_t$ = *n*x*n* covariance matrix at time *t, for a theoretical single species management portfolio only the diagonal of the covariance was used – ignoring correlations in species revenues was taken to be analogous to single species fisheries management where interactions between species are not explicitly considered in decision making.*

$\boldsymbol{\mu_t}$ = *n*x1 vector of expected revenues at time *t*

R_t = target revenue at time *t*

$w_{i,t}$ = a species *i* element of $\boldsymbol{w_t}$

$W_{i,t}$ = maximum weight for species *i* at *t* (biological constraint)

$\forall i$ = for all species

The steps taken to calculate the frontiers are as follows:

1. ***Select portfolio assets (i.e., species)***
    a. Ensure consecutive years of data for each species. Aggregate species where required and appropriate
    b. Select time period for portfolio

Because we applied methods used in the finance sector to fisheries stocks portfolios, adjustments to the VaR model are necessary to account for ecological and policy constraints and variability of fisheries stocks. Minimum and maximum revenue weights should be set to reasonable levels based on historical patterns in revenues and policy constraints. For example, allowing the minimum revenue weight ($w_{i,t}$) of a stock to be 0, would be equivalent to allowing the fishery for that species to be closed. In finance, a buyer can borrow money to buy shares of an asset (stock, bond, etc.) such that revenue weights derived from optimization can exceed historic weights. An analogous increase in revenue weights for harvest fisheries species is unlikely to be sustainable, so a sustainability parameter is used to constrain the maximum revenue weights in the optimization. Finally, external environmental conditions influencing fishery stock production that existed in the past may have changed in the present, thus past revenues in a portfolio should be down- weighted for the optimization.

To make these adjustments for this analysis, we did the following:

2. ***Set the parameters including:***
    a. the biological constraints (i.e., minimum, and maximum harvest weights to constrain the revenue weights for each species at time *t*).
        i. A sustainability parameter (ɣ) can be used in setting the maximum weight for species *i* at *t.* We set ɣ = 1 but it could be lowered by fisheries management to control harvest levels.
    b. decay factor (λ) to down-weight earlier data in the timeseries. We used λ = 0.741 which results in 5% of the data remaining after 10 years. If λ=1, all data are given equal weight.

Minimum harvest weights were set to zero. Maximum harvest weights *(*$W_{i,t}$) were set as the maximum annual harvest for each species attained between the beginning of the time series until time *t*:

$$W_{i,t} = \frac{\gamma_{i,t} B_{i,t}}{\Omega_{i,t}} \qquad \text{Eqn. 2}$$

Where:

$$\Omega_{i,t} = \frac{\sum_{k=1}^{t} \lambda^{t-k+1} p_{i,k} y_{i,k}}{\sum_{k=1}^{t} \lambda^{t-k+1} p_{i,k}} \qquad \text{Eqn. 3}$$

$\gamma_{i,t}$ = the sustainability parameter for species *i* at time *t*
$B_{i,t}$ = maximum sustainable catch equal to the maximum catch up until time *t* for each species
$\Omega_{i,t}$ = weighted average catch over time (including decay) for species *i* at time *t*
λ = decay factor set at 0.741
$p_{i,k}$ = price of species *i* at time *k*
$y_{i,k}$ = catch quantity

3. *Calculate the covariance matrix of revenue*

Each element of the covariance matrix ($\sum_{i,j,t}$) is calculated as the covariance of revenue between species *i* and *j* (or variance if species *i* = *j*) at time *t* (Eqn. 4 & 5). λ is incorporated into each element (Eqn. 4).

$$\sum_{i,j,t} = \frac{\sum_{k=1}^{t} \lambda^{t-k+1}(r_{i,k}-\mu_{i,t})(r_{j,k}-\mu_{j,t})}{\sum_{k=1}^{t} \lambda^{t-k+1}} \qquad \text{Eqn. 4}$$

Where:

$$\mu_{i,t} = \frac{\sum_{k=1}^{t} \lambda^{t-k+1} r_{i,k}}{\sum_{k=1}^{t} \lambda^{t-k+1}} \qquad \text{Eqn. 5}$$

$r_{i,k}$ = revenue of species *i* at time *k*
$\mu_{i,t}$ = expected revenue of species *i* at time *t* (an element of μ_i; Eqn. 1)

4. *Select the target revenues to generate the frontier from.*

a. We generated 20 targets from the distribution of annual revenues from the beginning of the time series up until time *t*. We also ensured the annual revenue for time *t* was included for calculating the risk gap.

5. *Use a quadratic optimization algorithm (ipop in the "kernlab" package) to solve Eqn. 1 for each target revenue and each frontier type:*

a. The portfolio frontier is calculated using the full covariance matrix
b. The species frontier is calculated using the diagonal of the covariance matrix (Sanchirico *et al.* 2008).

The solution of the quadratic optimizer provides the optimal weights/variance (0–1) for each species in the portfolio—within the constraints provided—that minimize the risk associated with achieving each target revenue.

To plot the realized revenue with the frontier:

6. *Calculate the risk taken to achieve the realized revenue using the implicit revenue weights and the covariance matrix. This equates to point "b" on Figure 1 and is calculated using the first numerator of Eqn. 6.*

The risk gap was calculated as follows:

a. Use the optimal weights and the covariance matrix to calculate the minimized risk to achieve the same realized revenue on the portfolio frontier. This equates to point "a" on Figure 1 using the second numerator of Eqn. 6.
b. Subtract the optimal risk from realized risk to determine the risk gap.
c. Divide the risk gap at time *t* by realized revenue at time *t* to calculate risk gap per dollar (Eqn. 6 denominator)

The risk gap (g_t) is calculated as the distance between point b and a (Fig. 1) on the frontier plots, which correspond to the numerators in Eqn. 6 respectively:

$$g_t = \frac{\sqrt{\tilde{\boldsymbol{w}}_t{}' \sum_t \tilde{\boldsymbol{w}}_t} - \sqrt{\hat{\boldsymbol{w}}_t{}' \sum_t \hat{\boldsymbol{w}}_t}}{\tilde{\boldsymbol{w}}_t{}' \boldsymbol{\mu}_t} \qquad \text{Eqn. 6}$$

Where $\widetilde{\boldsymbol{w}}_{\boldsymbol{t}}$ is the vector of implicit revenue weights (revenue in time *t*/weighted revenue in time *t*) that were chosen to obtain the realized revenue and $\widehat{\boldsymbol{w}}_{\boldsymbol{t}}$ is the vector of optimal revenue weights estimated by the quadrative optimizer to achieve the target revenue $R_t = \widetilde{\boldsymbol{w}}_{\boldsymbol{t}}{}'\boldsymbol{\mu}_{\boldsymbol{t}}$.

Results

Data Selection and Processing

Landed weight and revenue of NEFMC managed species varied over time in total magnitude and species relative contribution (Figures 2 and 3). There was a declining trend in overall landings through the time series but an increase in revenue driven by sea scallops. Aggregations of species in the dataset were denoted by "**" in the NMFS name, SKATES, RAJIDAE (FAMILY) **. Species-specific reporting for council managed skate species is limited to 2004 and later (Figure 4), and all seven skate species currently managed by the New England skate complex are managed together, so all species-specific reports were aggregated with SKATES, RAJIDAE (FAMILY) ** to produce a longer consecutive time series for portfolio analysis and are hereafter referred to as "SKATE". Catch records for SKATE, ROSETTE (*Leucoraja garmani*) appeared in the dataset between 2007–2009, 2015 and 2019 but were listed as confidential so omitted from the dataset.

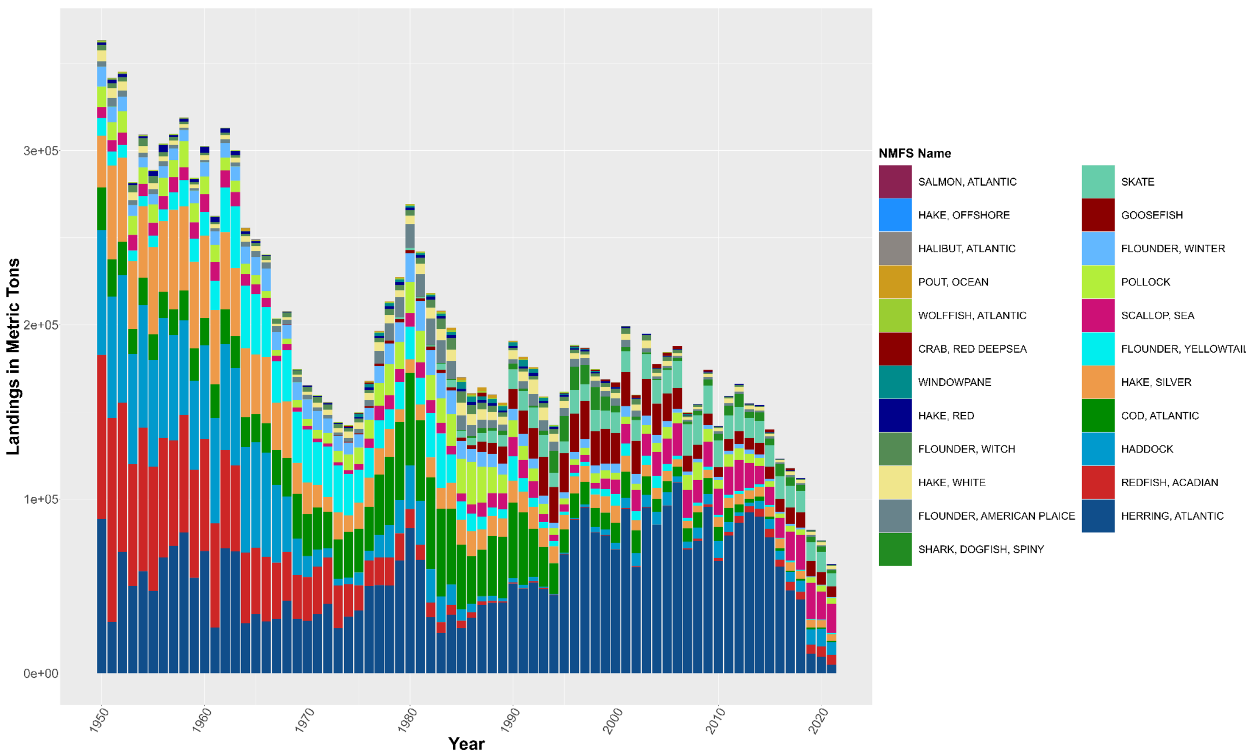

Figure 2. Landings Weight (Metric Tons) for all species managed under a fishery management plan (FMP) by the New England Fisheries Management Council. As skates have historically been aggregated through the entirety of the time series with species-specific reporting appearing only recently all council managed skate species were combined with the historical aggregation as "SKATE".

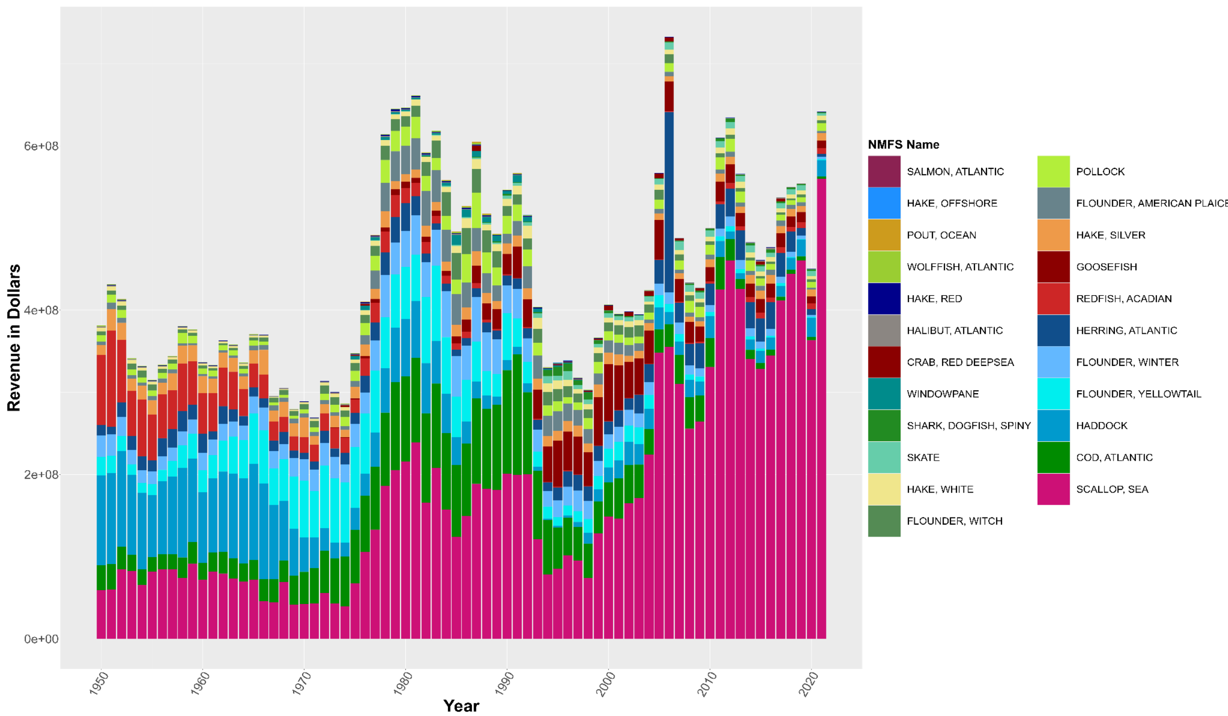

Figure 3. Landings In Revenue (Dollars Standardized to 2021 Value) for species managed by the NEFSC.

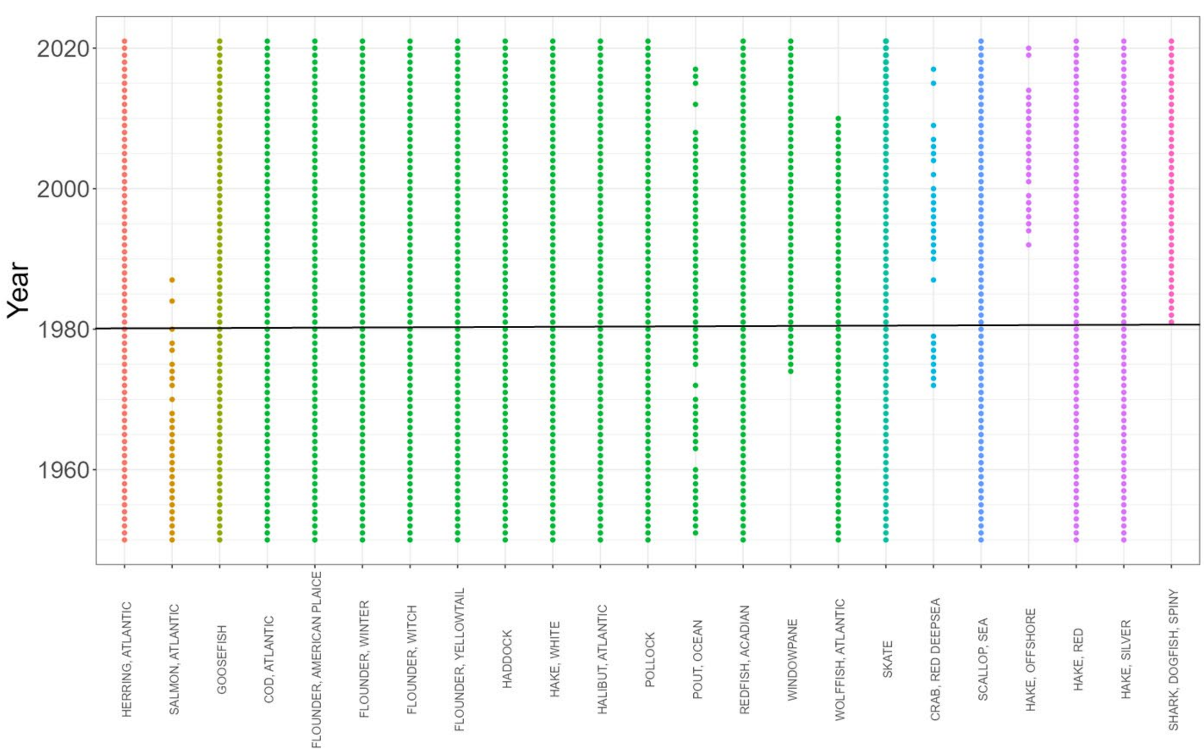

Figure 4. Availability of annual landings and revenue for species managed by NEFSC. Colors represent Fishery management Plans. Data below the line was not included in the frontier analysis.

Catch records for species with data gaps (SALMON, ATLANTIC, CRAB, RED DEEPSEA and HAKE, OFFSHORE) were removed from the portfolio and the time series was truncated to 1981, prior to which SHARK, DOGFISH, SPINY were not recorded in the dataset. This resulted in a dataset with consecutive years of data required for the portfolio analysis, representing species from seven of the nine New England Fishery Management Plans. POUT, OCEAN and WOLFISH, ATLANTIC were no-possession species towards the end of the time series, so we included them in the portfolio analysis with zeros applied for landings and revenue in those years.

Effective risk management relies on negative correlations in revenue among species. Correlations in revenue were generally positive among species managed under the Northeast Multispecies Fishery Management Plan, but other species managed by NEFMC were negatively correlated with groundfish thus diversifying the covariance in the portfolio (Figure 5).

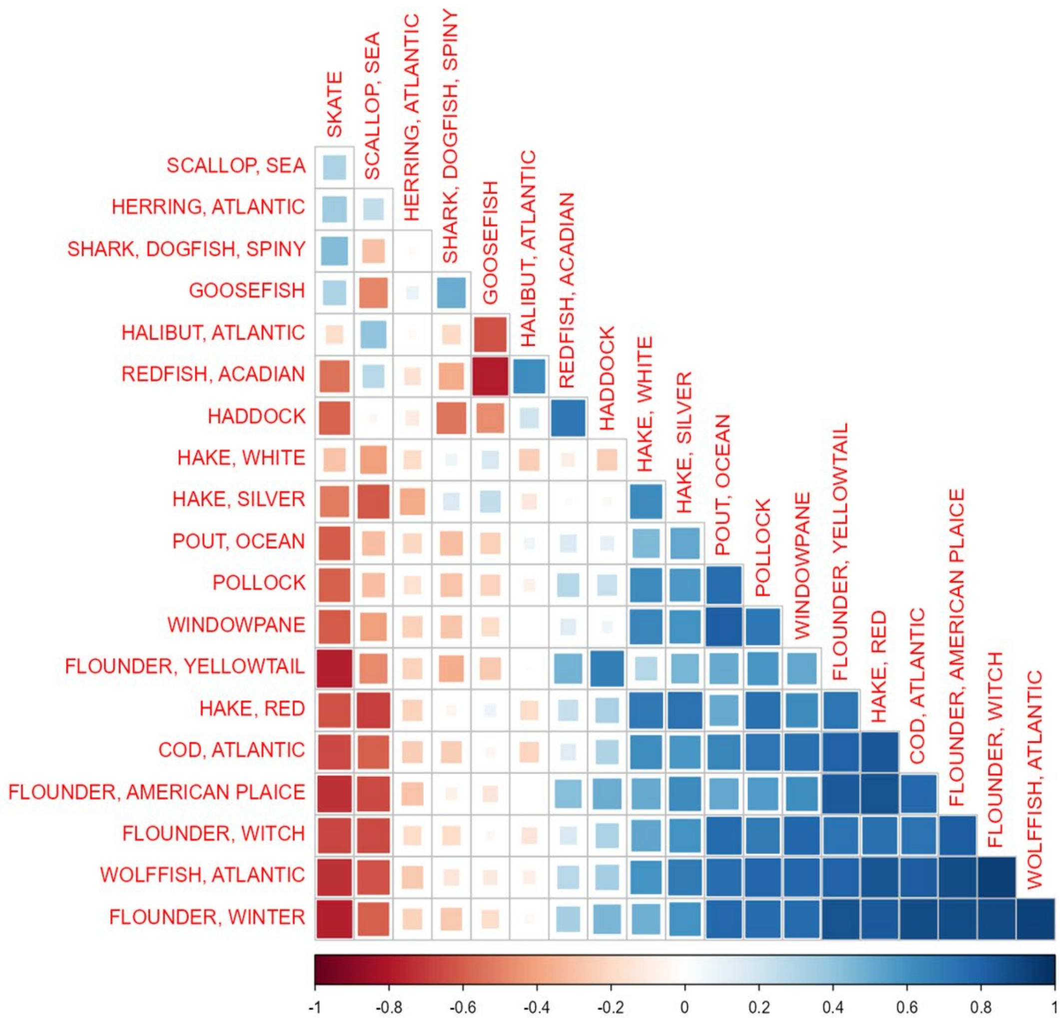

Figure 5. Correlation of annual revenue (1981-2021) among NEFMC managed species that were included in the portfolio. Note: landings and revenue data for skates were aggregated for the frontier analysis.

Frontier Analyses

We present two forms of frontier plots: one adopted by Jin *et al.* (2016; Figure 6) and one adopted by Sanchirico *et al*. (2008; Figure 7), which show annual and long-term portfolios, respectively. In Figure 6, we incorporated λ=0.741 and the biological constraint is the maximum annual landing for each species up until time *t.* Note there is a 10 year “burn-in” (1981–1990) period due to using λ=0.741, after which point the realized revenue falls further from the multispecies frontier suggesting the same amount of revenue could have been achieved with less risk, or more revenue could have been obtained for the same level of risk. The risk gap derived using the Jin *et al*. (2016) method generally increased until a peak in 2006, then gradually decreased (Figure 8). The peak resulted from a spike in herring prices, driven by a change in perception of stock size (Shepherd et al. 2009), a decrease in allowable catch, and a demand for herring bait. Figure 7 shows the frontier generated from the whole time series. It does not incorporate a decay factor (i.e., λ=1 so each year of the time series contributes equal weight to the frontier) and the biological constraint is the maximum annual catch for each species during the entire period.

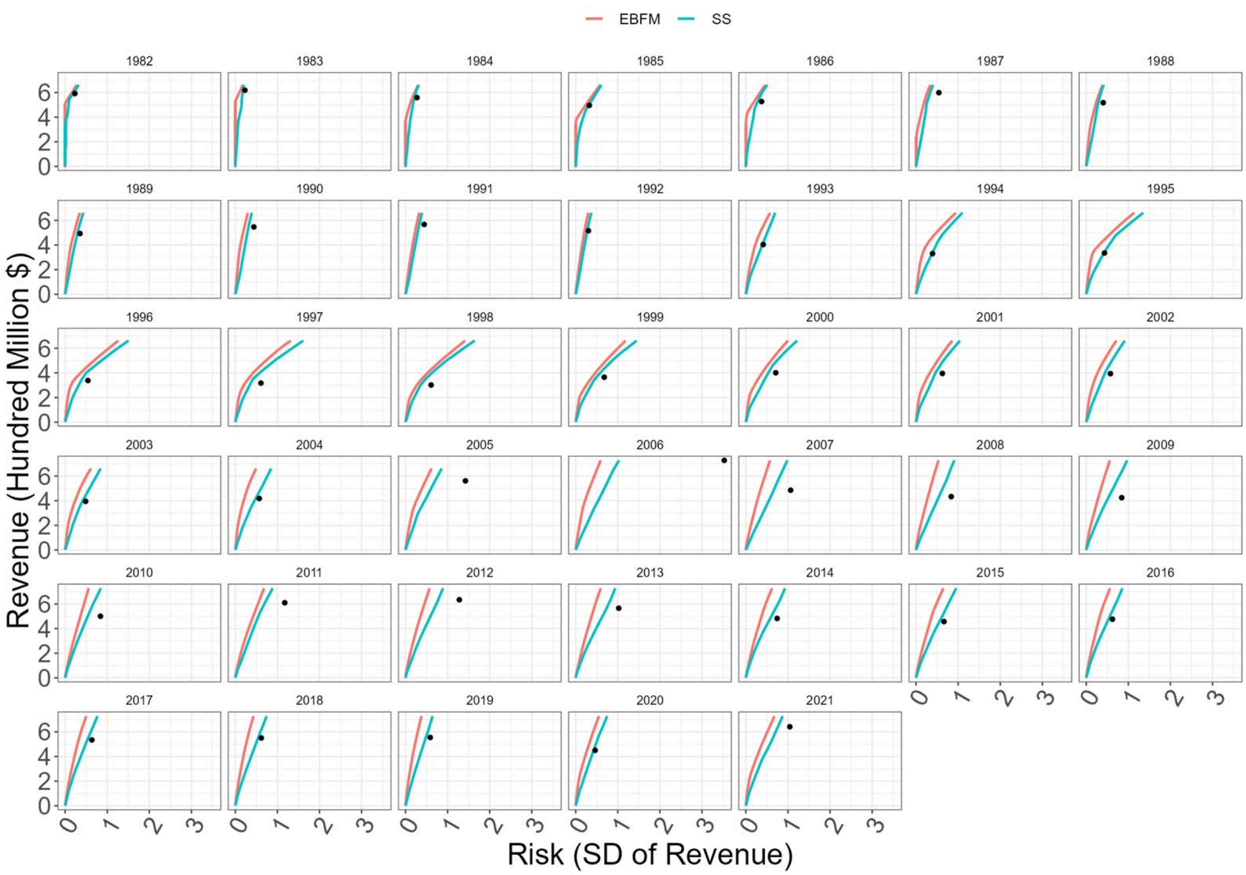

Figure 6. The realized revenue (dot) and multispecies-based fishery management (EBFM, red line) and single species management (SS, blue line) efficient frontiers for each year of the timeseries. The vertical axis depicts the expected revenue (in 2021 dollars) and the horizontal axis depicts risk (measured as standard deviation of revenue). Note: this method of displaying efficient frontiers incorporates a decay factor to down-weight older data and the biological constraint is maximum landings up to year t.

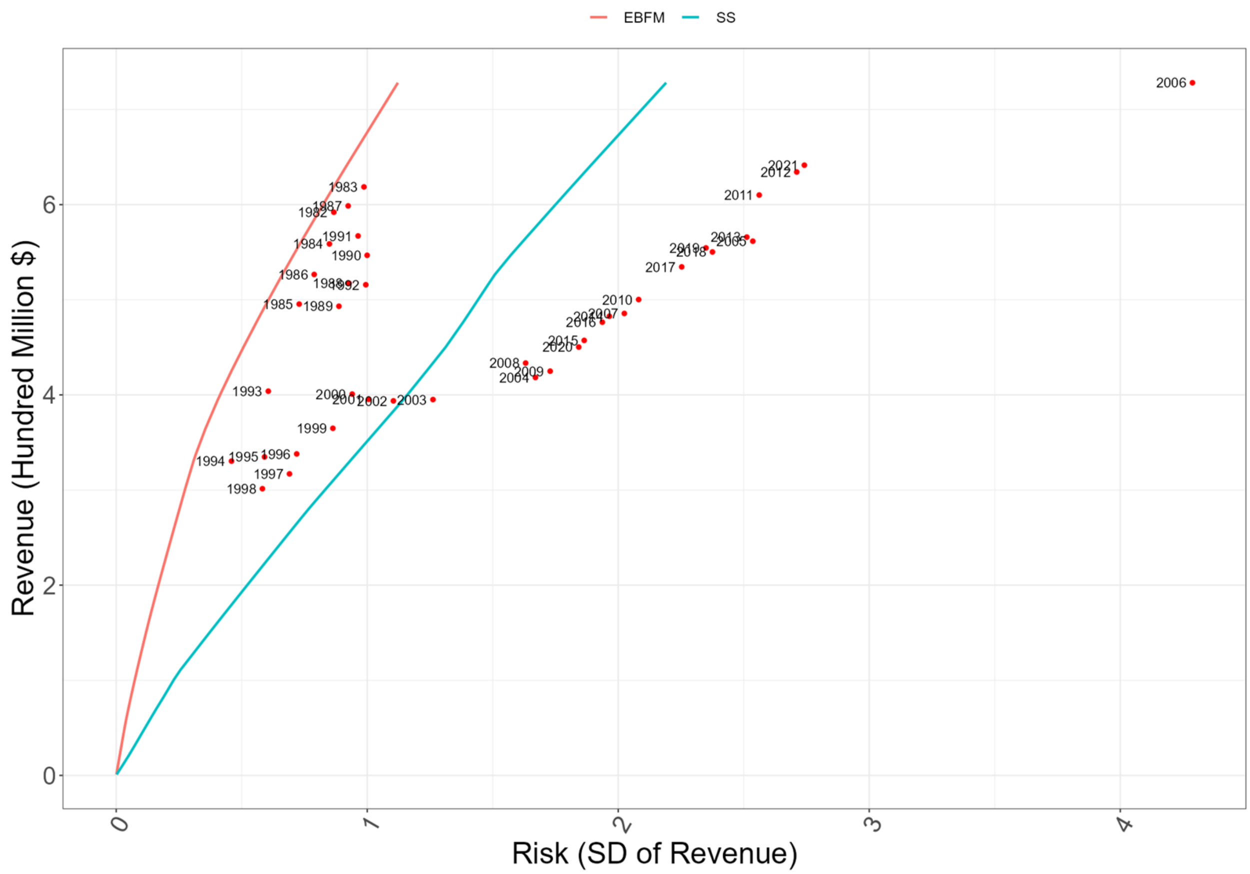

Figure 7. The actual portfolios for each year of the timeseries(dot) and ecosystem based fishery management (red line) and single species management (blue line) efficient frontiers generated . The vertical axis depicts the expected revenue (in 2021 dollars) and the horizontal axis depicts risk (measured as standard deviation of revenue). Note: this method of displaying efficient frontiers treats all annual revenue values with equal weighting (i.e., no decay factor) and uses the maximum landings for the time period (1981-2021) as the biological constraint.

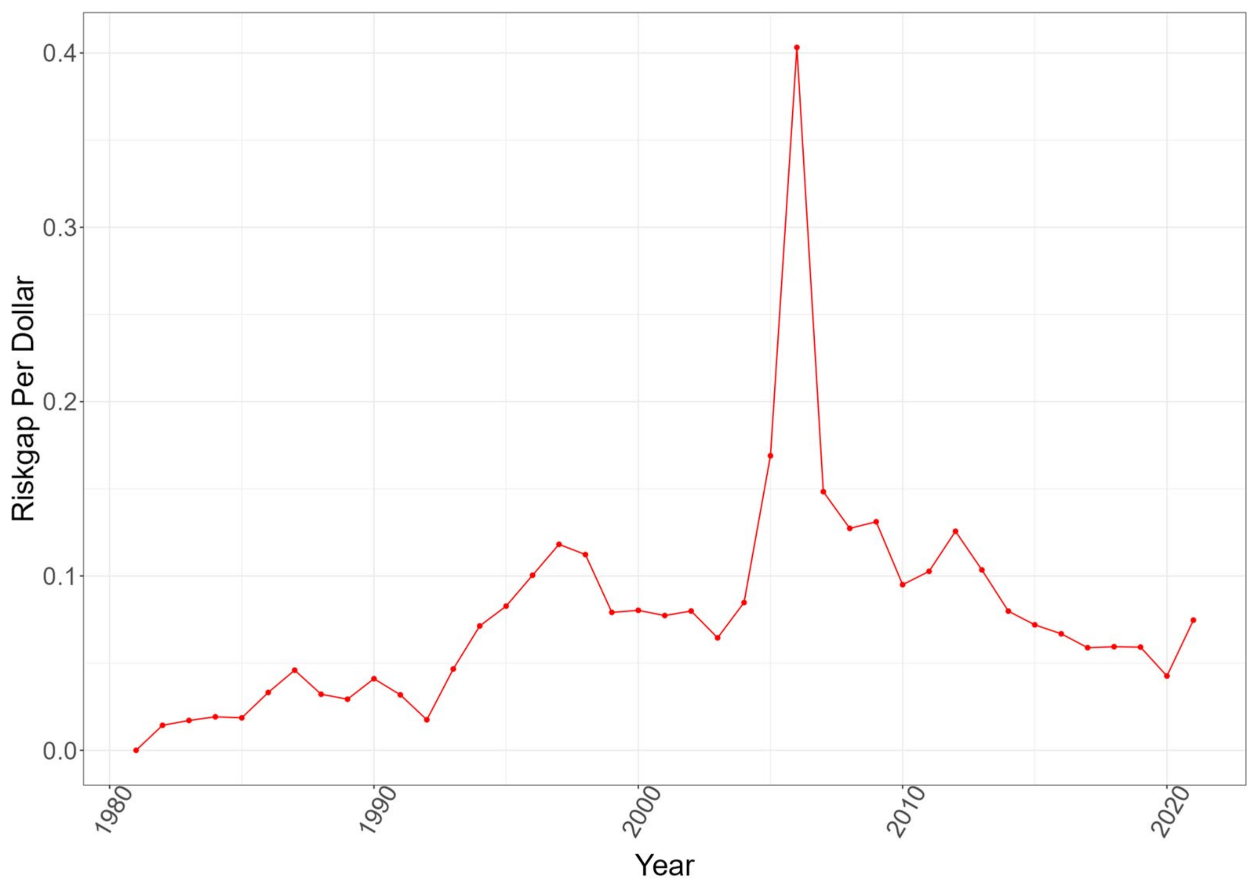

Figure 8. The difference in risk (per dollar) taken to achieve the realized revenue (point b in Figure 1) for each year of the time series, versus the minimized risk that would have been assumed to achieve that same revenue (point a in Figure 1) using the portfolio approach.

Discussion

Results suggest that portfolio diversity relies on coordinated management of groundfish and other species. There was strong positive covariance in revenue among groundfish species, but negative covariance with scallops, skates and monkfish. With this diversity and negative covariance in revenue, economic frontier analysis of the example portfolio indicated that the same amount of revenue could have been achieved with less risk of foregone yield, or more revenue could have been obtained for the same risk. This example demonstrates that management systems benefit by allowing for flexibility to harvest abundant species by considering constraints of management strategies and tactics.

Although the demonstration used publicly available data, extensive data processing was required prior to frontier analysis. For example, inconsistent taxa labels required re-coding. Historical species aggregations were phased out and replaced with more species-specific labels. Therefore, landings of some species were reaggregated and combined to extend the time series with historical aggregation. Missing data (i.e., years with no landings or revenue) was another challenge. We considered five potential solutions for each species with missing data: exclude the taxa from the analysis, aggregate taxa, truncate the time series, interpolate, or add ‘true zeros’ for missing landings. We excluded three species from the portfolio, aggregated skates, and truncated the time series to 1981. Truncating the time series to 1981 allowed for characterization of current fishery conditions while leaving enough data so that historical trends could also be characterized. Had a more recent year been chosen to truncate the time series, we would not have been able to have a historical reference to the state of past fishery conditions for these species (e.g., cod). Replicating these analyses with confidential disaggregated data (e.g., merged dealer and vessel trip reports) would provide a more comprehensive series of landings and revenue (e.g., no missing records that were masked in the publicly available data), allow for more disaggregated taxa that are expected to add more covariance for optimization, and support sub-regional analyses (e.g., the Georges Bank ecological production unit, Lucey & Fogarty 2013).

The New England Fishery Management Council could also explore alternative multispecies portfolios for evaluation of efficiency frontiers. Our demonstration included Council managed species, but that could be expanded to include other important species that New England fishermen can target (e.g., American lobster, squids) or more restrictive portfolios (e.g., groundfish, monkfish, skates and dogfish). The theoretical basis of portfolio management relies on technical interactions (species caught by the same fishing gear) or ecological interactions that produce asynchronous trends and negative covariance in annual landings or revenue. Other portfolio combinations could be explored, but similar diversity in covariance should generally produce similar results.

Risk gaps are intriguing to consider. Per pound of fish caught, or dollar of revenue earned, they inform us how much risk of foregone yield was undertaken relative to what could have optimally occurred. In all instances, the risk gap was greater than zero, meaning there was more risk incurred in capturing that amount of fish. This result implies that though there is some risk involved in executing a fishery, it could be less. It also implies that the value of the fisheries being landed could be higher. Why the risk gap peaked in 2006 in this region is attributable to many factors (e.g., demand for herring bait), but even apart from that peak, the risk of the fisheries portfolio has increased in New England over time.

We are continuing to refine the frontier analysis to improve optimizer tolerance and precision and determine the sensitivity of the frontier to these parameters, and would welcome any suggestions to improve the approach. Model convergence at narrower tolerances or increased precision is dependent on portfolio composition, the decay factor, and the selected time series. Additional constraints (e.g., a decay factor for biological constraints) could be explored to better handle portfolios with declining revenue time series.

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