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

A DEMONSTRATION FOR SOUTH ATLANTIC 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 the South Atlantic snapper-grouper complex to show that these estimates are feasible with publicly available data. There was a general increase in total landings and revenue from the 1950s to the 1980s driven primarily by black sea bass, golden tilefish, porgies, and groupers, followed by decreases in landings and revenue in the last four decades. Economic frontier analysis for 1991–2021 of the South Atlantic snapper-grouper portfolio indicated that the observed 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 multispecies fishery management (e.g., allowing access to multiple target species, with fewer constraints) to decrease 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).

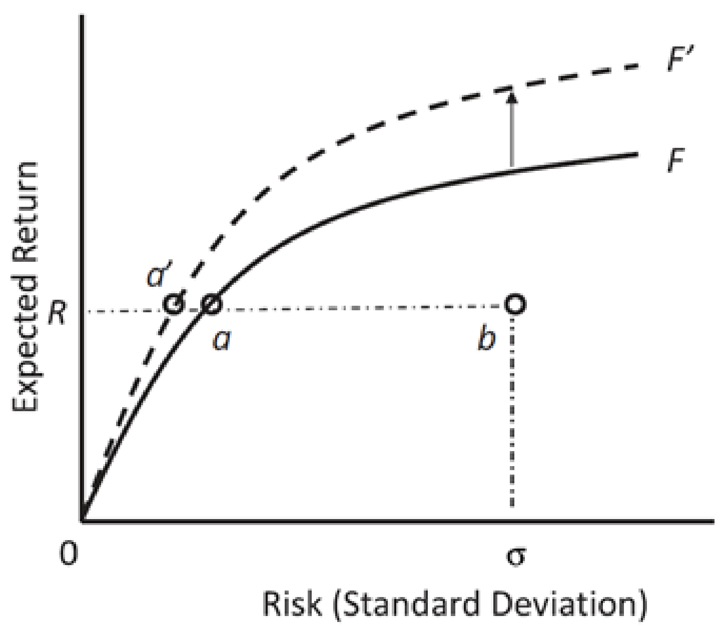

Figure 1. The efficient frontier and the risk gap in which R represents a given level of total revenue; F and F' are two efficient frontiers single species and ecosystem-based fisheries management); b denotes the actual portfolio; a and a' denote the optimal portfolios on F and F'. The distance between 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 with 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 South Atlantic snapper-grouper fisheries to show that portfolio analyses are feasible with the available data and can be considered for fishery management. Species in the snapper grouper complex are targeted by the same fleets (e.g., MacLauchlin Buck 2018, Overstreet et al. 2018) and have some common trends in productivity (Wade et al. 2023). Using commercial data, we developed a portfolio for this complex, and although we recognize that recreational landings are a key part of these fisheries, we did not have access to the recreational data for this demonstrated example. The demonstrated example can be modified and extended with feedback from the South Atlantic Fishery Management Council (SAFMC), its Scientific and Statistical Committee and Socioeconomic Panel.

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 South Atlantic 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. Publicly available data include commercial landings and revenue and recreational for-hire catch. Although it would be ideal to include all catches for species in a portfolio, revenue of recreational catch and landings from private or shore modes are not in the database. So, we focused on commercial landings. We also removed all records marked “confidential” with no landings and revenue data.

Frontier analysis requires consecutive years or data, so 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’ in the case of no possession species in a given year. 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 in the snapper-grouper complex.

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.

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

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
$\sum_{\boldsymbol{t}}$ = *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

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).

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

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)

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.

3. ***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:

4. ***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:

$$g_t = \frac{\sqrt{\widetilde{\boldsymbol{w}}_{\boldsymbol{t}}{}' \Sigma_t \widetilde{\boldsymbol{w}}_{\boldsymbol{t}}} - \sqrt{\widehat{\boldsymbol{w}}_{\boldsymbol{t}}{}' \Sigma_t \widehat{\boldsymbol{w}}_{\boldsymbol{t}}}}{\widetilde{\boldsymbol{w}}_{\boldsymbol{t}}{}' \boldsymbol{\mu}_{\boldsymbol{t}}} \qquad \text{Eqn. 6}$$

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

Multispecies landings and revenue varied over time in total magnitude and species contribution (Figures 2 and 3). There was a sharp increase in both from the 1950s to the 1980s followed by a decline in overall landings through the end of the time series. The increase in landings appears to be driven by black sea bass, golden tilefish and the historic aggregations of porgy and grouper. Catch records for three species (cottonwick grunt, longspine porgy, and saucereye porgy) appeared in the dataset, but were listed as confidential so were omitted from the dataset.

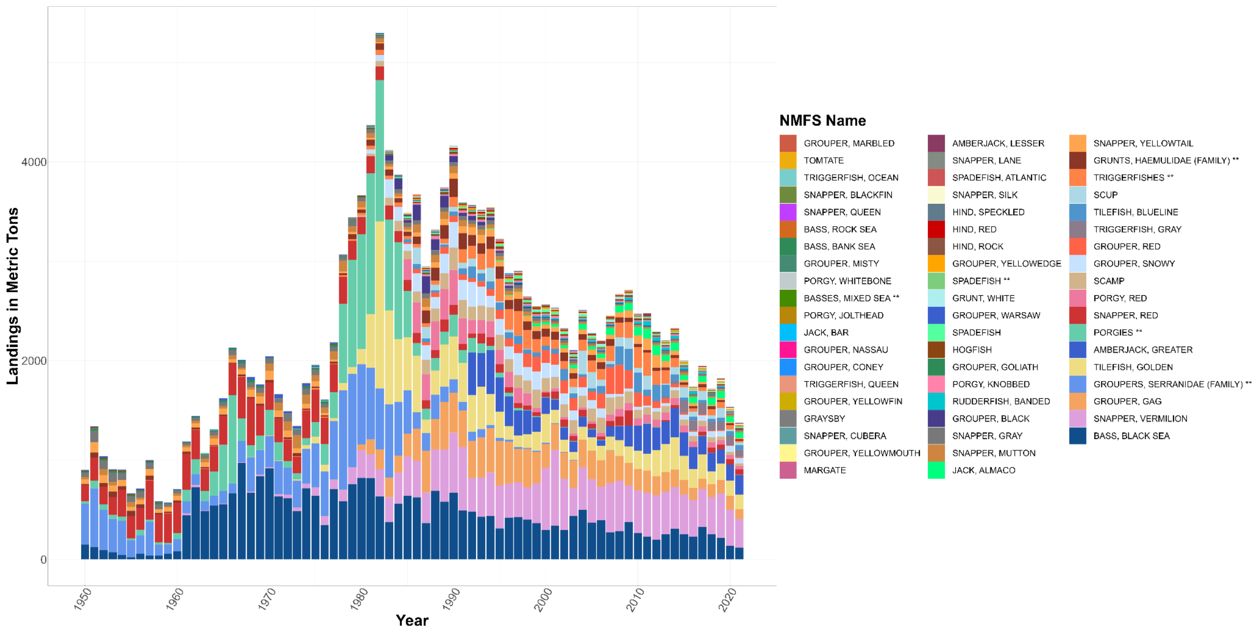

Figure 2. Landings Weight (Metric Tons) for species considered in the South Atlantic snapper-grouper complex portfolio.

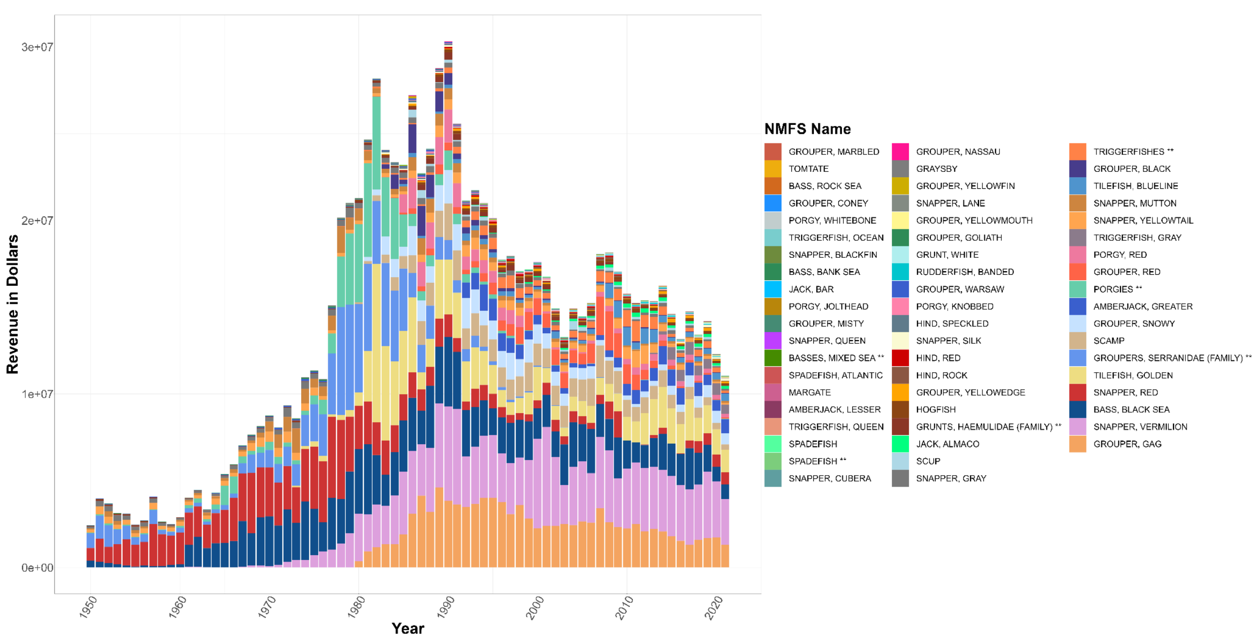

Figure 3. Revenue (Dollars Standardized to 2021 Value) for species considered in the South Atlantic snapper-grouper complex portfolio.

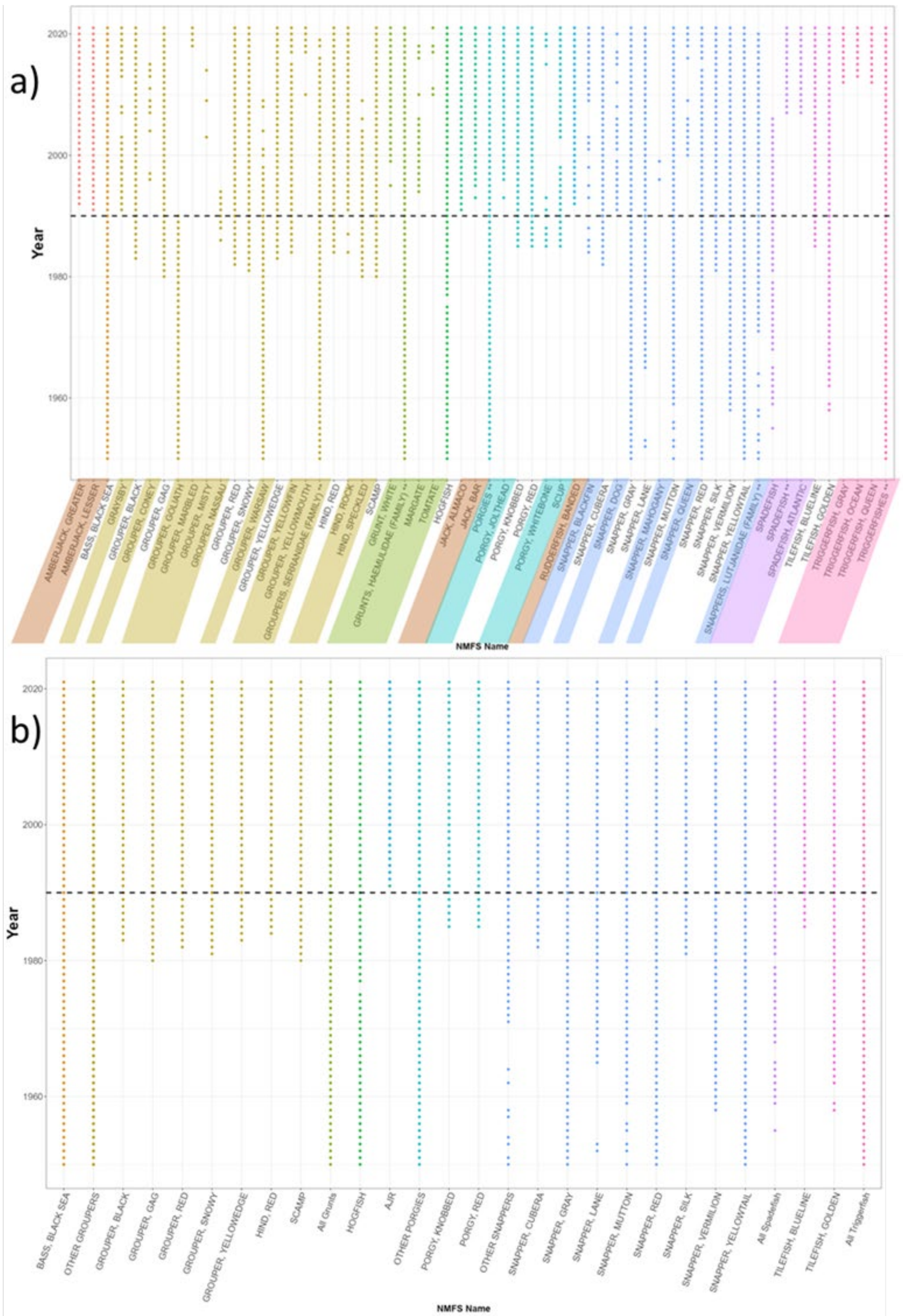

Figure 4. Availability of annual landings and revenue data for species in the South Atlantic snapper-grouper complex a) before and b) after data decisions. Dot colors represent the Fishery Management Plan each taxa are managed under. Data on and below the dotted line (i.e., pre-1991) were not included in the frontier analysis. The colored name labels on the x-axis in (a) show species that were aggregated together to produce a longer time-series.

The South Atlantic snapper-grouper complex encompasses a diverse array of species. We initially examined these species further by dividing them into major species groups: Groupers, Snappers, Porgies, Grunts, Triggerfish, Spadefish, Amberjacks, Jacks, Rudderfish, Bass, Tilefish, and Hogfish. Aggregations of species in the dataset were denoted by "**" in the NMFS name (e.g., GROUPERS, SERRANIDAE (FAMILY) **) (Figure 4a). Species-specific reporting for council managed species is limited to 1980. In many instances, few catch records are available with many data gaps present (Figure 4a). Frontier analysis requires consecutive years of data, so several data decisions were made to address these data gaps. Many taxa with data gaps present were evaluated on a case-by-case basis.

When consecutive records of species-specific data were present for council managed species, we isolated those records, but if council managed species with limited records were present they were recombined into their respective historical aggregations. This approach was taken to address the missing species-specific data for some species of Groupers, Snappers, and Porgies; these aggregations were denoted "OTHER" for their respective species group (e.g., "OTHER GROUPERS"). Wreckfish is managed with an individual transferable quota and has spatial separation from the other groupers, so it was not included in the aggregation, and due to limited data was excluded from the analysis.

Aggregation was used to address the missing data gaps for grunts, spadefish, amberjacks, jacks, and rudderfish. Species specific reports for grunts, triggerfish, and spadefish were recombined with the respective historical aggregate to eliminate missing data gaps and are hereafter referred to as "All Grunts", "All Triggerfish", and "All Spadefish" respectively. The landings of amberjacks, jacks, and rudderfish were also aggregated and are referred to as "AJR" or "jacks". Species-specific reports which had consecutive years of data present in the dataset were isolated when possible. In some instances, the remaining records for other council managed species-specific reports and their respective historical aggregation were too limited and still possessed data gaps even after aggregation and so were dropped (e.g., Bass, Tilefish). The time series was then truncated to 1991 to remove any remaining data gaps.

Effective risk management relies on negative correlations in revenue among species. Correlations were generally positive among species in the snapper-grouper complex. However, different trends in revenue for Triggerfish, Silk Snapper, Blueline Tilefish, "Jacks" (including Amberjacks and Rudderfish), Spadefish, Yellowedge Grouper, and Red Grouper produced strong negative correlations (Figure 5).

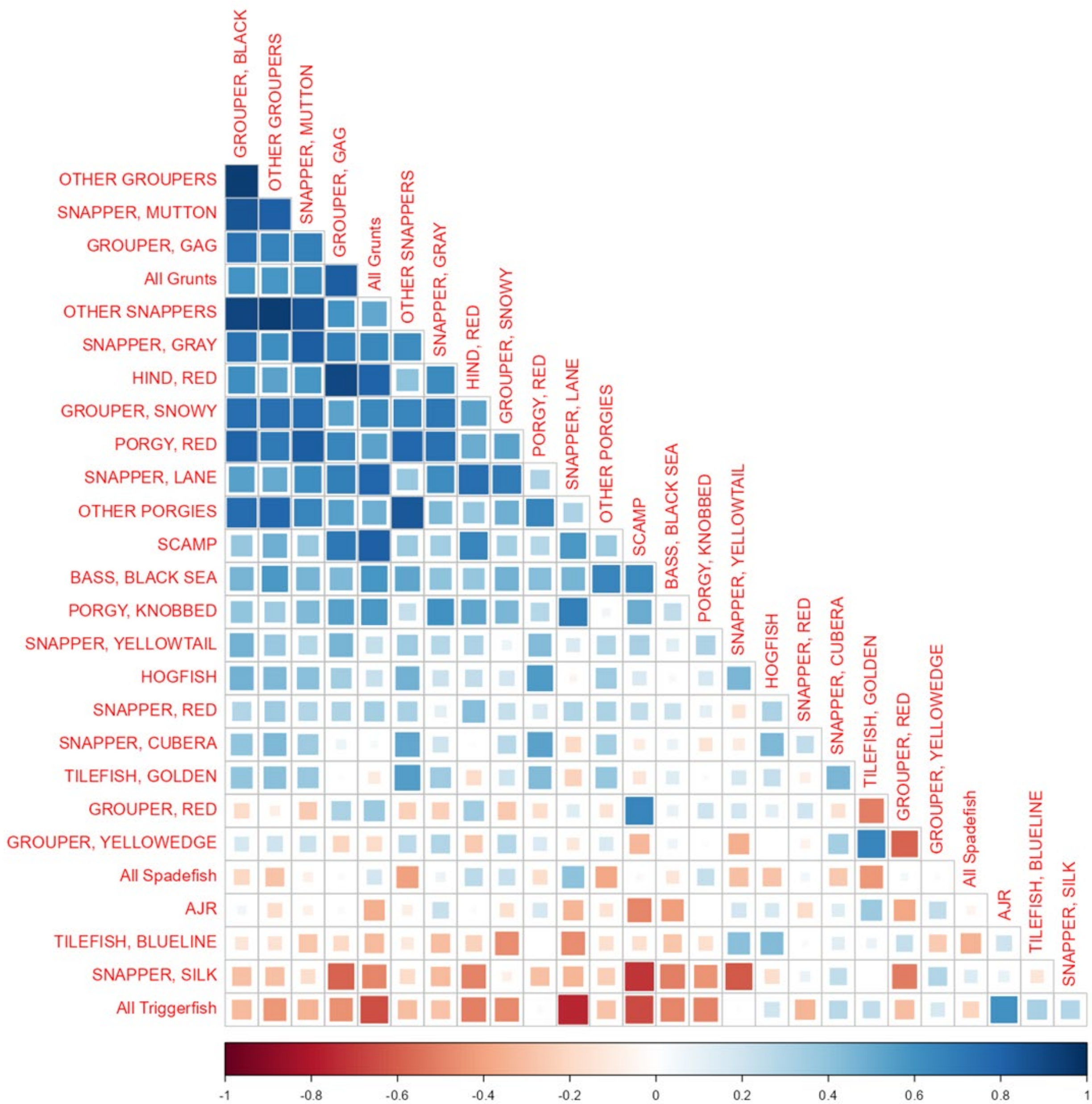

Figure 5. Correlation of annual revenue (1991-2021) among snapper-grouper species.

<u>Frontier Analyses</u>

We present two forms of frontier plots: one adopted by Jin *et al.* (2016; Figure 6) and another adopted by Sanchirico *et al*. (2008; Figure 7), which show annual and long-term portfolios, respectively. In Figure 6, we incorporated a decay factor of 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" (1991–2000) period due to using λ=0.741. Particularly in the middle of the timeseries, 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. 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. The risk gap derived using the Jin *et al*. (2016) method generally increased to a peak in 2008 then decreased (Figure 8 and 9).

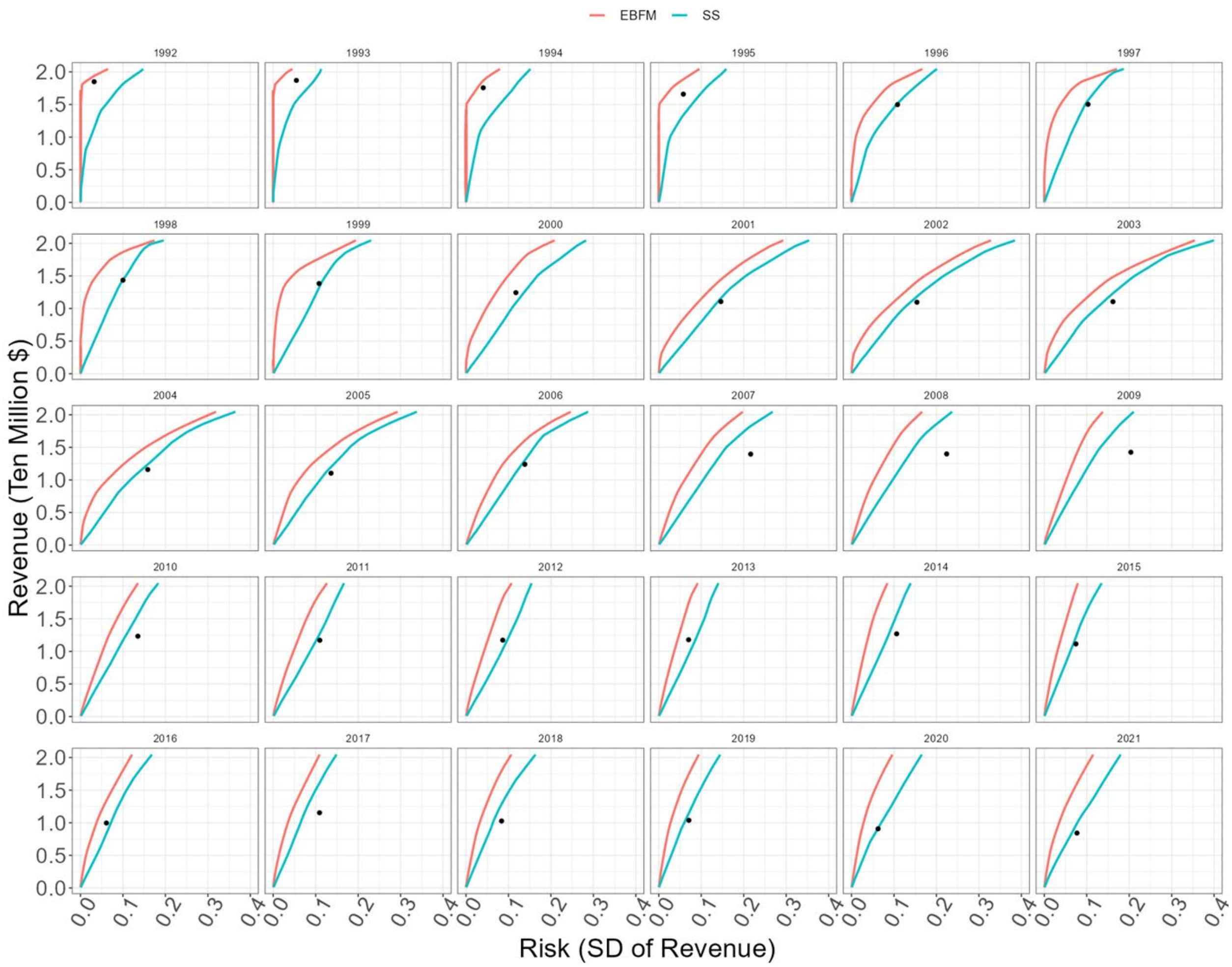

Figure 6. The realized revenue (dot) and multispecies-based fishery management (EBFM, red line) and single species management (SS, blue line) efficient frontiers for each year of the timeseries. The vertical axis depicts the expected revenue (in 2021 dollars) and the horizontal axis depicts risk (measured 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.

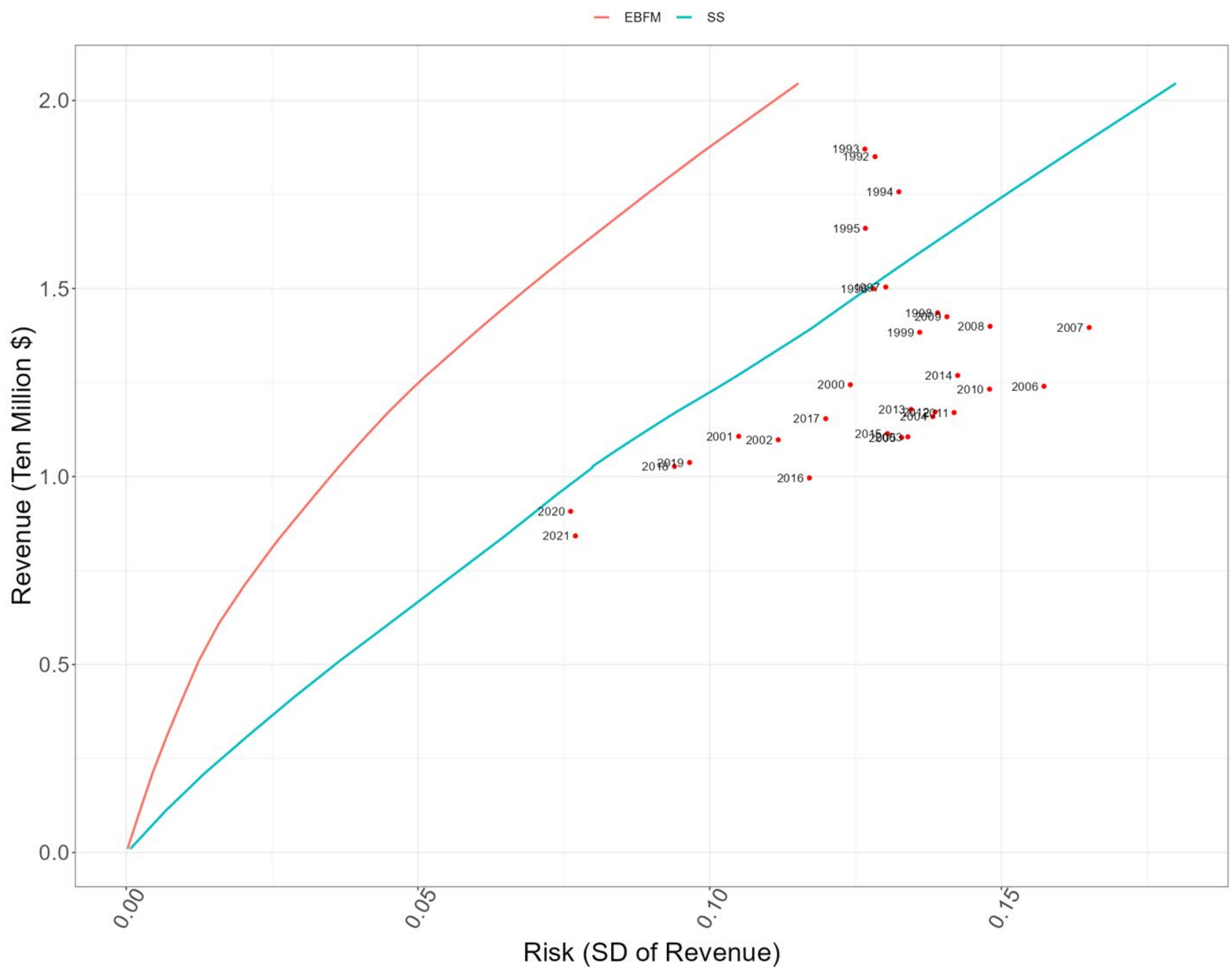

Figure 7. The actual portfolios for each year of the timeseries (dot) and ecosystem based fishery management (red line) and single species management (blue line) efficient frontiers generated . The vertical axis depicts the expected revenue (in 2021 dollars) and the horizontal axis depicts risk (measured 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 (1991–2021) as the biological constraint.

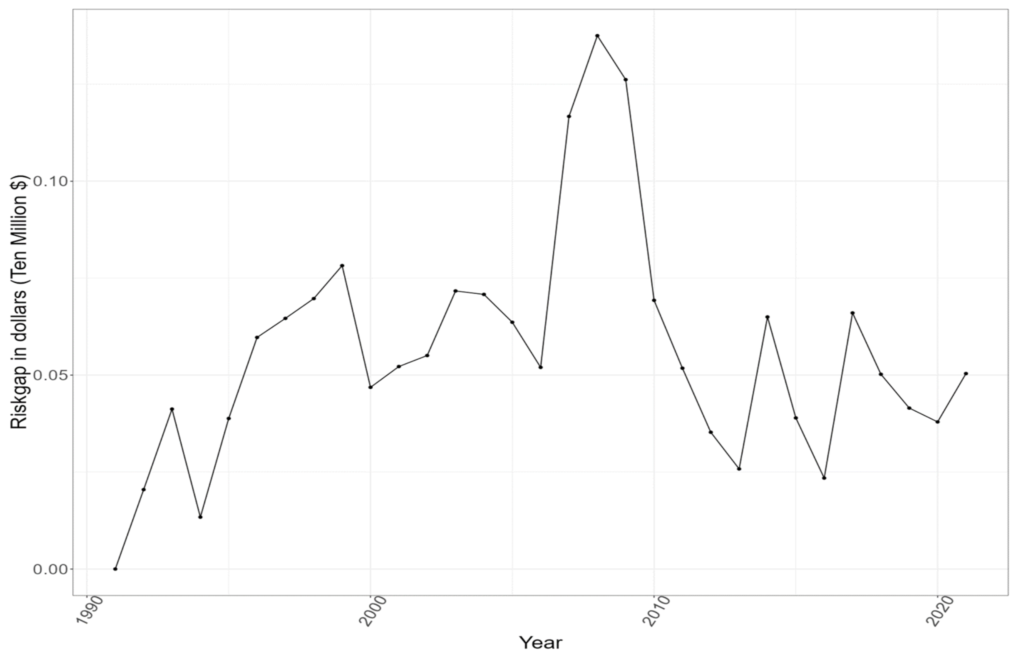

Figure 8. The risk gap in dollars i.e., the difference in risk taken to achieve the realized revenue (point b in Figure 1) for each year of the time series, versus the minimized risk that would have been assumed to achieve that same revenue (point a in Figure 1) using the portfolio approach. This risk gap is calculated from the numerator in Eqn 6.

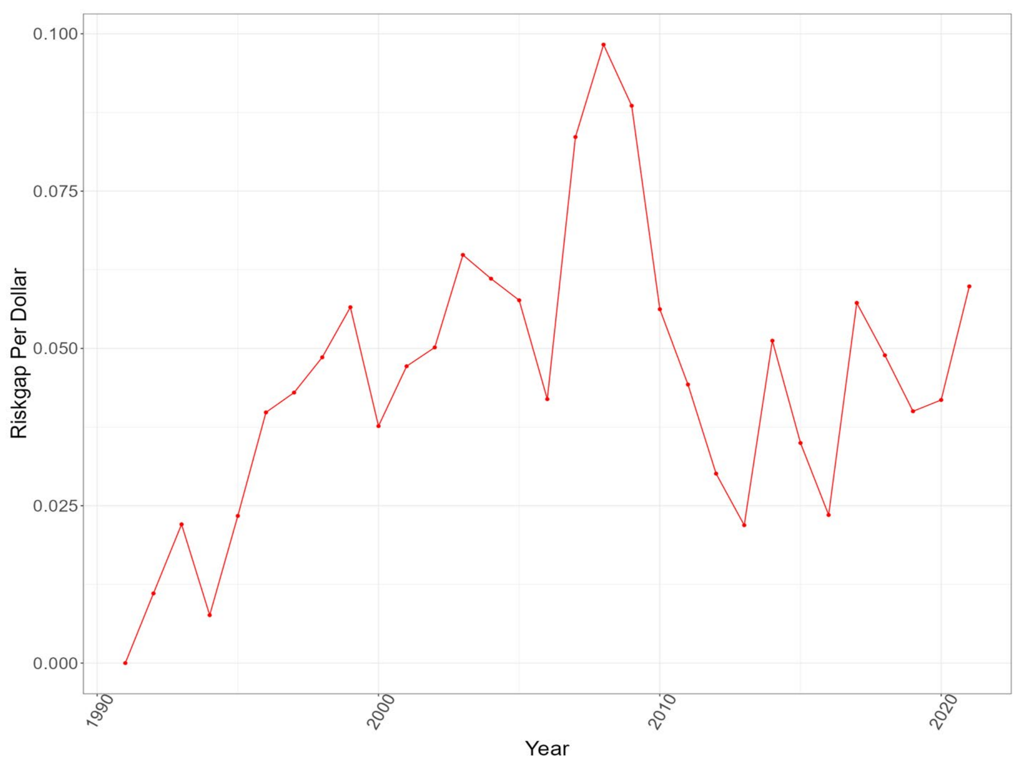

Figure 9. The risk gap per dollar calculated using Eqn 6. For example, in 2002 an extra five cents/dollar was risked than necessary to achieve the same revenue using the portfolio approach.

Discussion

Results suggest that portfolio diversity relies on coordinated management of snappers, groupers, and other species. Within the general decreasing trend of landings and revenue in the last four decades, there were contrasting trends in Triggerfish, Silk Snapper, Blueline Tilefish, "Jacks" (including Amberjacks and Rudderfish), Spadefish, Yellowedge Grouper, and Red Grouper. Because of these contrasting trends, frontier analysis suggests that the observed revenue could have been achieved with less risk, 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.

Risk gaps inform 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 2008 can be attributed to a range of factors, but overall there was no trend in the risk gap over time for this portfolio. With species-specific climate effects, we should expect different trends in productivity and even greater benefits from coordinated portfolio management.

Ideally, all catches and revenues of species in the portfolio are accounted for in the frontier analysis. However, no revenue data from the for-hire recreational fishery and no catch from private or shore modes of the recreational fishery were included in the publicly available data. Therefore, the demonstration is limited to landings and revenue from the commercial fishery. Although the analogy to financial portfolios can be applied at several levels, and access to multiple target species by commercial fishermen is analogous to investors, evaluating risk mitigation with coordinated management by the Council should include all catches in the analysis. Therefore, a next step for evaluating Council managed species would be to include estimates of total recreational catch and its economic value.

Extensive data processing was required for the publicly available data 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 (Cottonwick Grunt, Longspine Porgy, and Saucereye Porgy), and aggregated grunts, spadefish and triggerfish, and AJR or "jacks". We also truncated the time series to 1991, which allowed for characterization of current fishery conditions while leaving enough data so that historical trends could also be considered. 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. Replicating these analyses with confidential disaggregated data 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.

The South Atlantic Fishery Management Council could also explore alternative multispecies portfolios for evaluation of efficiency frontiers. Our demonstration included the South Atlantic snapper-grouper complex, but that could be expanded to include other important species that South Atlantic fishermen can target (e.g., blue crab) or more restrictive portfolios (e.g., deepwater species, grunts and porgies, jacks, shallow-water groupers, shallow-water snappers; MacLauchlin Buck 2018). The theoretical basis of portfolio management relies on technical interactions (i.e., species caught by the same fishing gear) or ecological interactions (e.g., predator-prey, competition), markets (e.g., product replacement) or management (e.g., regulatory constraints), 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.

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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