Portfolio Analysis

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SEDAR 103: US Caribbean Application of Alternate Assessment Methods

Summary

Portfolio analysis uses either commercial, recreational, or both types of landings data (both mass and value) to produce Portfolio Frontier Curves and risk gaps. Portfolio analysis can be used as a fisheries performance indicator, and as well as to evaluate risk and return of various management decisions in a range of management scenarios. However, the approach needs reliable economic data on catches (typically the catch value) but can be based on other measures that are not necessarily value. It would doable in the Caribbean context, but would entail investment in assurance of data quality.

I. Introduction

As with a financial stock portfolio, the emergent properties of a diverse portfolio of management units will be more stable than any one unit on its own. Portfolio approaches and theory have been explored for marine fisheries to mitigate risks (e.g., loss in revenue, overfishing, fishery efficiency, market shifts, catchability, climate change impacts, etc.). This approach represents a systemic treatment of all stocks or fisheries in an ecosystem and focuses on the aggregate dynamics of a group of management units (e.g., many species or populations). When examined theoretically, empirically, experimentally, and via simulations, portfolio management consistently produces better outcomes, including increasing the status and value of the resource, reducing risk, and improving buy-in from stakeholders and resource-users. Benefits include status of stocks, economic valuation, and business, stock and regulatory stability, all within current legal mandates. This approach can mitigate other pressures that were not initially foreseen.

The essence is that in composite, an efficiency frontier can be calculated using widely available data. And then at any given point in time, one can ascertain how far from the frontier, in terms of either value or risk, one is and adjust accordingly (Fig. 1). When ecosystem factors are considered, it is a more beneficial efficiency frontier.

Multispecies Portfolio Management

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. The studies also show that more aggregated estimates of efficiency frontier (F’) outperform single stock-based approaches (F; Figure 1 Jin et al. 2016).

Portfolio estimates for all regions are feasible in the U.S. using the National Marine Fisheries Service Landings database. Portfolio estimates demonstrate the relative benefits to meet the regulatory mandates of maintaining stock status, and can help to facilitate the implementation of ecosystem-based fisheries management (Figure 2; Townsend et al. 2024).

II. Method Description

Adapted from Brewster et al. (2025):

Portfolio analysis has several sequential steps: data acquisition, data preparation including selection of taxa in the portfolio, frontier analysis, and visualization for interpreting results. We describe methods in each stage with guidance based on the literature and our experiences (Edwards et al. 2004, 2005; Jin et al. 2016; Brewster et al. 2023 a,b).

A time series of fishery monitoring data by species or other taxonomic group is needed for portfolio analysis. The geographic or organizational scope of data can vary according to the portfolios being considered, because portfolio effects apply to multiple components of a fisheries system: an individual fisherman, a local fishing cooperative, a sole-owned fleet, a fishing organization, a fishing port, a coastal state, or a regional fishery management organization. For our demonstrations, data were downloaded from the publicly available National Marine Fisheries Service (NMFS) Landings database (NOAA Fisheries Office of Science and Technology, Commercial Landings Query, Available at: www.fisheries.noaa.gov/foss). These data are assumed to be a census of landings by geographic region, taxa, and fishing sector (commercial and/or recreational), reporting landings biomass, value (for commercial landings), and related information.

Any group of fish stocks that have technical, biological, market or regulatory interactions are expected to have portfolio effects. Portfolio selection should consider geographic extent (e.g., ecosystems, regional jurisdictions, fishing grounds of mixed-species fisheries), and species with technical interactions (i.e., species caught together), biological interactions (e.g., predators, prey, competitors), market interactions (e.g., common processing or supply chains, product replacement), and management interactions (e.g., available fishing locations or protected areas). Species with contrasting trends (i.e., negative covariance in the revenue time series) are needed to minimize risk to the portfolio. Other considerations include choosing a period that represents current conditions (e.g., fishery management system, ecosystem state, productivity regime), and data availability for each year, because frontier analysis requires consecutive years of revenue and landings data. Ultimately selecting species in a portfolio should be used to align management objectives with ecosystem structure.

We use the value-at-risk methodology from the J.P. Morgan RiskMetrics VaR model (J.P. Morgan/Reuters, 1996) to minimize risk (standard deviation of revenue) for desired target revenues. We calculated two efficient frontiers: a portfolio frontier representing ecosystem-based fisheries management that facilitates coordinated management of multispecies portfolios and a single species frontier that represents a conventional single species approach to fishery management, accounting for intraspecies variability but not interspecies interactions (Figure 1; red and blue lines throughout the examples). The frontiers were derived by using a quadratic optimization algorithm to solve Eqn 1 (in matrix notation), whereby optimal revenue weights are determined for each species that minimize the risk associated with attaining various target revenues (Figure 1), while accounting for biological constraints.

$$min_{w_t} w_t' \textstyle\sum_t \quad w_t \; s.t. \, w_t'\mu_t \geq R_t, w_{i,t} \leq W_{i,t} \; \forall i \qquad \text{Eqn 1}$$

Note: bold typeface indicates a vector or matrix

i = 1,…,n is the species index

w_t= vector of revenue weights calculated at time *t.* Revenue weights allow fishery managers to select the harvest 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 w_t

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

$\forall i$ = for all species

We use a mean-variance representation of expected utility, and thus a quadratic optimizer, due to its applicability across quite general conditions (Meyer, 1987) and its appropriateness in the study region (Jin et al. 2016). However, alternative specifications accounting for important higher moments of the distribution can, and should, be employed where necessary. We applied methods used in the finance sector to fisheries stocks portfolios, so adjustments to the VaR finance 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 values 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 may not be sustainable, particularly for stocks with a long exploitation history, so a sustainability parameter is used to limit the maximum revenue weights (Eqn 2) in the optimization as part of the biological constraint. Common practice has been to use a single parameter for the sustainability constraints. In this paper and others (Sanchirico et al. 2008; Carmona et al. 2020), sustainability has been a proportion of the maximum catch. This may be a conservative approach (particularly for some species that have been underexploited throughout the timeseries) but is appropriate for demonstration and for early stages of applying portfolio analysis to management. Alternative sustainability constraints could be based on factors that affect ecosystem productivity and fisheries landings (e.g., estimates of maximum economic yield from bioeconomic models that account for ecological, biological, economic, and management factors influencing stock productivity).

Finally, external conditions influencing fishery production that existed in the past (e.g., climate, markets) may have changed. In which case, past revenues in a portfolio should be down-weighted for the optimization (i.e., using a decay factor). The decay factor serves to minimize the importance of past years' revenues in the mean-variance optimization used to generate the efficient frontier (Figure 1) The application of a decay factor is dependent on the period of the analysis, the time step of the data, and factors that may have influenced fishing revenues. For example, if the analysis is being conducted on a portfolio of fish stocks for a period of a few years with monthly revenue data, then all data in the analysis may represent current conditions, and a decay rate need not be applied (i.e., λ=1). However, longer periods with an annual time step helps to inform interspecies interactions. In which case, the environmental conditions and management plans that allowed for catch experienced in early years may likely not exist in later years. Thus, when generating frontiers that may be used to guide management, the influence of early years on the optimization should be down-weighted to prevent optimal results that cannot be achieved under current conditions. Other authors (e.g., Jin et al. 2016, Sanchirico et al.

2008, Rădulescu et al. 2010) noted that exponential smoothing is one approach for handling external variability in conditions that influence productivity and other options should be considered such as autoregressive models of expected revenues. Jin et al. (2016) note that "Multiple drivers affecting the covariance matrix include ecological (food web trophic interactions), biological (fish stocks), and economic (market prices) effects, fishing operations and technologies (bycatch), and management (input and output controls, area management, etc.)". For increased realism, some of these factors could be incorporated into bioeconomic models and used to generate efficient frontiers. These models could also be used to project future conditions and likely changes in efficient frontiers (e.g., as fisheries production is influenced by climate). For this demonstration and for initial application of this approach to management, using exponential smoothing provides a conservative estimate of efficiency frontiers.

Steps for calculating portfolios are:

Set the parameters including:

i. the biological constraints (i.e., minimum, and maximum harvest weights to constrain the revenue weights for each species at time *t*). 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 the analyst/fisheries management to control harvest.

ii. decay factor (λ) to down-weight earlier data in the time series. If λ = 0.549, 5% of the data remains after five years; λ = 0.741, 5% of the data remains after 10 years. If λ=1, all data are given equal weight. We set λ=1 for demonstration. Note that the decay factor will impact the model's "burn-in" period.

Estimated frontiers are somewhat sensitive to changes in these parameters. Lowering the sustainability parameter will reduce the attainable revenue for a given risk and an increased decay rate will result in a frontier that better reflects current conditions. 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 1
$p_{i,k}$ = price of species *i* at time *k*
$y_{i,k}$ = catch quantity
The impact of the decay factor on the frontier depends on the trend in revenue. In this instance, where revenue increases throughout the time series, a lower decay factor (i.e., 0.549) results in a frontier where more revenue can be attained for a given risk level than when λ = 1. Conversely, applying a lower decay factor to a portfolio with a decreasing revenue trend throughout time would result in a frontier where less revenue can be attained for a given risk level.

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)

Select the target revenues to generate the frontier from.

We generated 20 targets across the distribution of total annual revenues (i.e., revenues corresponding to the 0th, 5th, 10th, …, 95th, 100th percentile) from the beginning of the time series up until time *t*. We also ensured the annual revenue for time *t* was included as a target for calculating the risk gap (see section 4e) and provided a sequence of values between zero and the value at the 0th percentile to generate full frontiers that start with zero revenue and risk

Use a quadratic optimization algorithm to solve Eqn 1 for each target revenue and each frontier type:

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

To solve Eqn 1 we used the ipop quadratic programming solver from the "kernlab" package (Karatzoglou et al. 2022; based on the LOQO software Vanderbei 1999). This requires setting convergence tolerances ("margins" in ipop function) to determine how close the solution gets to the constraints. The analyst should consider the order of magnitude of the revenue when doing this. If the tolerances are too low, the algorithm may have difficulty finding a solution. If the tolerances are too large, the solutions might not be meaningful. For example, if a portfolio revenue is $\$10^6$, and the tolerances are 10^2, then the effective revenue is $\$10^6 \pm \$10^2$. Derived quantities (like the risk gap) should be greater than $\$10^2$ to be meaningful rather than a function of the tolerance. For this demonstration we set tolerances to 10^2 of the target revenue.

The solution of the quadratic optimizer provides an optimal revenue weight for each taxon ($\widehat{w}_{i,t}$) in the portfolio—within the constraints provided—that minimizes the risk associated with achieving each target revenue in the frontier (Figure 1). The optimal revenue weights are used to calculate taxon-specific landings, calculated as:

$$\widehat{w}_{i,t}\Omega_{i,t} \qquad \text{Eqn 6}$$

And taxon-specific optimal revenue ($\hat{r}$; which when summed for all taxa equals R_t):

$$\hat{r}_{i,t} = \widehat{w}_{i,t}\mu_{i,t} \qquad \text{Eqn 7}$$

The risk (as standard deviation of revenue) associated with each target revenue is calculated using the vector of optimal weights ($\widehat{w}_t$) and the covariance matrix:

$$\sqrt{\widehat{w}_t{}' \textstyle\sum_t \quad \widehat{w}_t} \qquad \text{Eqn 8}$$

After the minimized risk associated with each target revenue has been calculated, the frontier curves can be plotted. Using many target revenues in the optimization loop enables the analyst to produce a smoother portfolio. However, independent optimizations at multiple target revenues increase the chance that solutions will be singular. If the optimization algorithm is not able to find the solution and it impedes frontier construction, an analyst can consider adjusting the composition of the portfolio, changing the revenue scale, time series, or number of targets in the optimization loop, or increasing the tolerances. We encountered convergence issues for some portfolio configurations, input parameters and optimization constraints. In such instances, we skipped target revenues that had singular solutions (using the “tryCatch” function in base R) and moved on to the next so it did not impede our ability to generate appropriate frontiers. After portfolio selection and prior to running the frontier analysis, revenue values should be scaled. Doing so changes the order of magnitude of the variables and constraints to be more favorable for computation. In this demonstration, we scaled all our values between 0–1 by dividing by the largest species/taxon maximum annual revenue Thus, after optimization, these values should be re-scaled to their original magnitude.

Calculate the risk taken to achieve the observed revenue using the vector of implicit revenue weights ($\widetilde{w}_t$) and the covariance matrix.

This equates to point “b” in Figure 1 and is calculated as:

$$\sqrt{\widetilde{w}_t{}' \textstyle\sum_t \quad \widetilde{w}_t} \qquad \text{Eqn 9}$$

Where implicit weights are calculated as:

$$\widetilde{\boldsymbol{w}}_{\boldsymbol{t}} = \frac{r_{i,t}}{\mu_{i,t}} \qquad \text{Eqn 10}$$

Determine risk gaps:

Several risk gaps (measures of excessive risk-taking; Figures 1) can be calculated as the difference in risk between:

a. the observed revenue and the same revenue on the single species frontier (Figure 1, point a; Eqn 11) which represents the reduction in risk between opportunistic fishing without consideration of within species variation in revenue versus accounting for optimized within-species revenue (Carmona *et al*. 2020; risk gap one);
b. the observed revenue and the same revenue on the portfolio frontier (Figure 1, point a; Eqn 11) which represents the risk reduction that could have been achieved by implementing the EBFM approach (Jin et al. 2016; risk gap two);
c. the two frontiers which demonstrates the value of accounting for species interactions and quantifies the improvement of using a portfolio approach over an optimized single species approach (Carmona et al. 2020; risk gap three). We calculated this at the realized revenue value for each year of the time series.

$$\boldsymbol{g}_{\boldsymbol{t}} = \frac{\sqrt{\widetilde{\boldsymbol{w}}_{\boldsymbol{t}}{}' \Sigma_{\boldsymbol{t}} \quad \widetilde{\boldsymbol{w}}_{\boldsymbol{t}}} - \sqrt{\widehat{\boldsymbol{w}}_{\boldsymbol{t}}{}' \Sigma_{\boldsymbol{t}} \quad \widehat{\boldsymbol{w}}_{\boldsymbol{t}}}}{\widetilde{\boldsymbol{w}}_{\boldsymbol{t}}{}' \boldsymbol{\mu}_{\boldsymbol{t}}} \qquad \text{Eqn 11}$$

Where $\widetilde{w}_t$ is the vector of implicit revenue weights that were chosen to obtain the observed revenue and $\widehat{w}_t$ is the vector of optimal revenue weights estimated by the quadrative optimizer (for either the single species or EBFM frontier) to achieve the target revenue $R_t = \widetilde{w}_t{}'\mu_t$. To calculate risk gap three the implicit weights in Eqn 11 are replaced with the optimal weights from the single species frontier. All risk gaps can be expressed as an absolute or relative risk (per dollar) value through the exclusion/inclusion of the denominator in Eqn 11.

Visualizing Results

Two methods have been used to visualize the frontiers in relation to the annual observed revenues. Sanchirico et al. (2008) presented a “snapshot” style plot (that does not include a decay factor i.e., λ = 1) that simultaneously depicts all observed revenues against the frontier for the entire time series and where the frontiers are calculated using a biological constraint equal to the maximum catch throughout the time series (Figure 2). Jin et al. (2016) presented a multi-panel plot that shows how the frontier updates with the integration of each additional year (Figure 3) and adjusts the biological constraints so that it is equal to the maximum catch up until time *t*. Each has strengths and limitations. The snapshot style plot, while providing a simple visual aid, can be misleading, particularly when generated from a lengthy time series. The frontier is generated using target revenues and a covariance matrix calculated from the full time series and so for direct comparison, the risk associated with each annual observed revenue should be calculated using the same covariance matrix. However, that may not reflect the risk that was assumed in earlier years because the constraints may have changed. This can be partially overcome by splitting the time series into chunks, with breakpoints based on catch composition (as in Sanchirico et al. 2008), management regime shifts etc. Alternatively, it may be more appropriate to calculate the risk using the covariance matrix up until time *t* (as is done in the multi-panel plot) but this does not allow for direct comparison with the full-time series single frontier. Thus, the multi-panel plot shows a more direct comparison of frontiers and observed revenue through time (and thus a more appropriate risk-gap) but is arguably harder to digest.

Frontier results need to be considered in the context of constraints. For example, some observed revenues may occur above the frontier, suggesting that more revenue could have been achieved for the same risk which appears to violate financial portfolio theory. Further, some observed revenues assume risk that extends beyond where the frontiers end, thus not producing a portfolio revenue value for that level of risk. Both situations occur because of the biological constraint parameter which affects the frontier, but not the observed revenue and associated risk (Jin et al. 2016; Carmona et al. 2020). Alternatively, an observed revenue occurring above the frontier could be the result of the tolerance of the optimization, which may need to be reduced. Finally, if the portfolio primarily comprises species with strong positive correlations, the single species frontier could potentially outperform (i.e., be situated to the left and above) the portfolio frontier (Sanchirico et al. 2008). This is because the actual risk is not assessed fully by the single species frontier (i.e., in this case the risk would have a downward bias when assessed using only the diagonal of the covariance matrix).

To achieve target revenue at lower risk as suggested by the EBFM frontier fishery managers need to know what quantity of each species/taxa contributes to the target revenue with minimized risk (i.e., the optimal revenue weight share for each taxa). Revenue weight shares (0–1) are calculated for a target revenue as:

$$\frac{w_{i,t}}{W_{i,t}} \qquad \text{Eqn 12}$$

If a taxa's revenue weight share is zero, it should not be landed; whereas if it equals one, that taxa should be harvested at its maximum harvest rate (i.e., at the biological constraint) to achieve the target revenue with minimized risk. We can assess past performance by comparing optimal and implicit revenue weight shares for each taxon for a given revenue.

A. Data Inputs

- Landings data (both mass and value),
- Either commercial or recreational (or both)
- Can be done using other, non-economic value information (e.g. effort, trips, other non-monetary value, etc.) but those are less common

B. Analyses/Data Outputs

- Portfolio Frontier Curves
- Risk gaps

C. Implications for Management

- Potential Fisheries Performance Indicator
- Useful to evaluate Mgt Scenarios
- Direct evaluation of risk and return for regional fisheries economies

D. Caveats

- Needs reliable economic data, typically value, of catches
- Hinges upon veracity of landings data
- How fish stocks are combined, selected, and used is important
- Verifying time series and taxonomy is important
- Verifying units and stock choices is important
- Show in aggregate for all SS, or use EBFM considerations?
- Show over time (Fig. 3), or composite for a decade (Fig. 2)
- Declination of value over time needs to be compensated for
- Again, can be based off of other measures
- Collaboration with regional experts is essential for understanding species interactions, management decisions and appropriate data and model decisions.
- There are tradeoffs in data decisions (taxa selection and time series) for feasibility and economic benefits, and representing current conditions.

III. Applications of the Method

- Has been presented to SAFMC SSC and related committees
- Has been presented to NEFMC SSC
- Being considered as a fisheries performance indicator by those Councils
- Other Councils are exploring them
- Beginning to be reported in Ecosystem Status Reports in various regions

IV. Discussion

Portfolio analysis is a complement to other assessment approaches and can address tradeoffs directly. The code for this, while evolving, is publicly available. The approach has been reviewed and being considered by NEFMC and SAFMC SSCs.

This approach fosters the need for flexible access (i.e. permits) to allow for targeting of germane taxa across a range of species to maximize returns/minimize risk. This approach has been considered as a means to facilitate climate resilient fisheries. This approach can accommodate transboundary or highly migratory fisheries, but that poses challenges for all fisheries that are largely managed via a place-based perspective.

We recommend that if sufficient data exists, that these be calculated for only the top 10-20 taxa and used in conjunction with other methods. The outputs are not designed to be used as a SDC or BRP for multispecies or the entire ecosystem, but can be used to track overall performance of the full fisheries management system. The one main caveat to overcome is not so much economic valuation, but consideration of artisanal or recreational data in the Islands context.

V. References

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VI. Tables and Figures

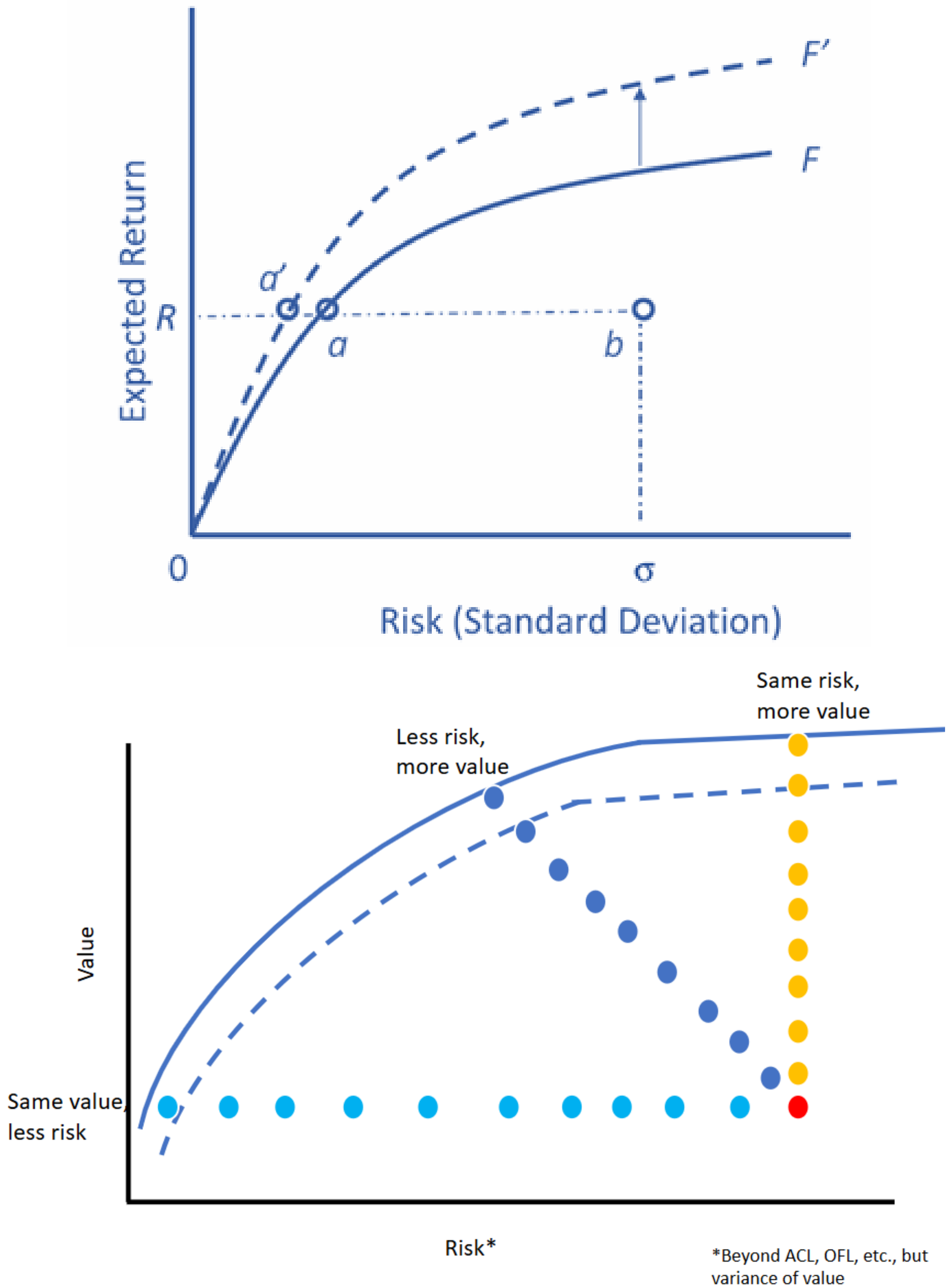

Figure 1. Portfolio frontier and designation of risk gap (a to b; top panel) and simplified version depicting the tradeoff in value and risk of any given fishery portfolio.

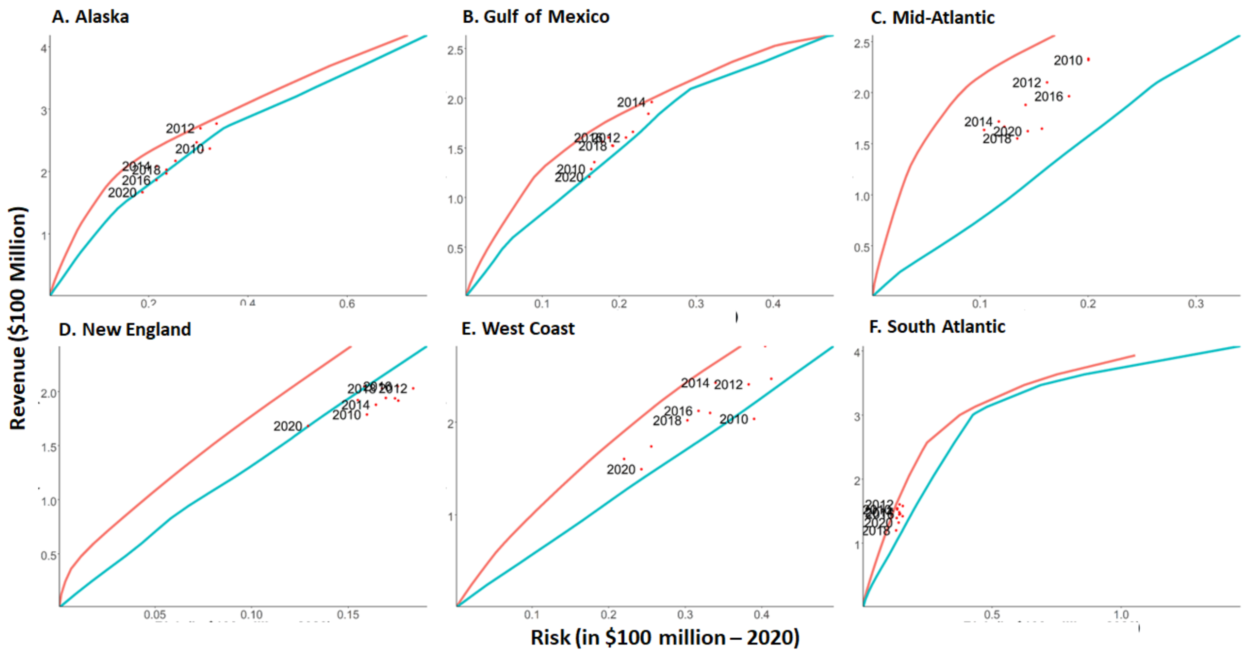

Figure 2. The single species and ecosystem--based fisheries management efficiency frontiers for the top 25 of all landed species (by revenue) for all regions, depicted in the Sanchirico et al. (2008) style plots. The actual portfolio values are from the past 15 years (not all 30 years in the time series) and the frontiers are for the terminal year. (A) Alaska, (B) Gulf of Mexico, (C) Mid--Atlantic, (D) New England, (E) West Coast, (F) South Atlantic. From Townsend et al. (2024).

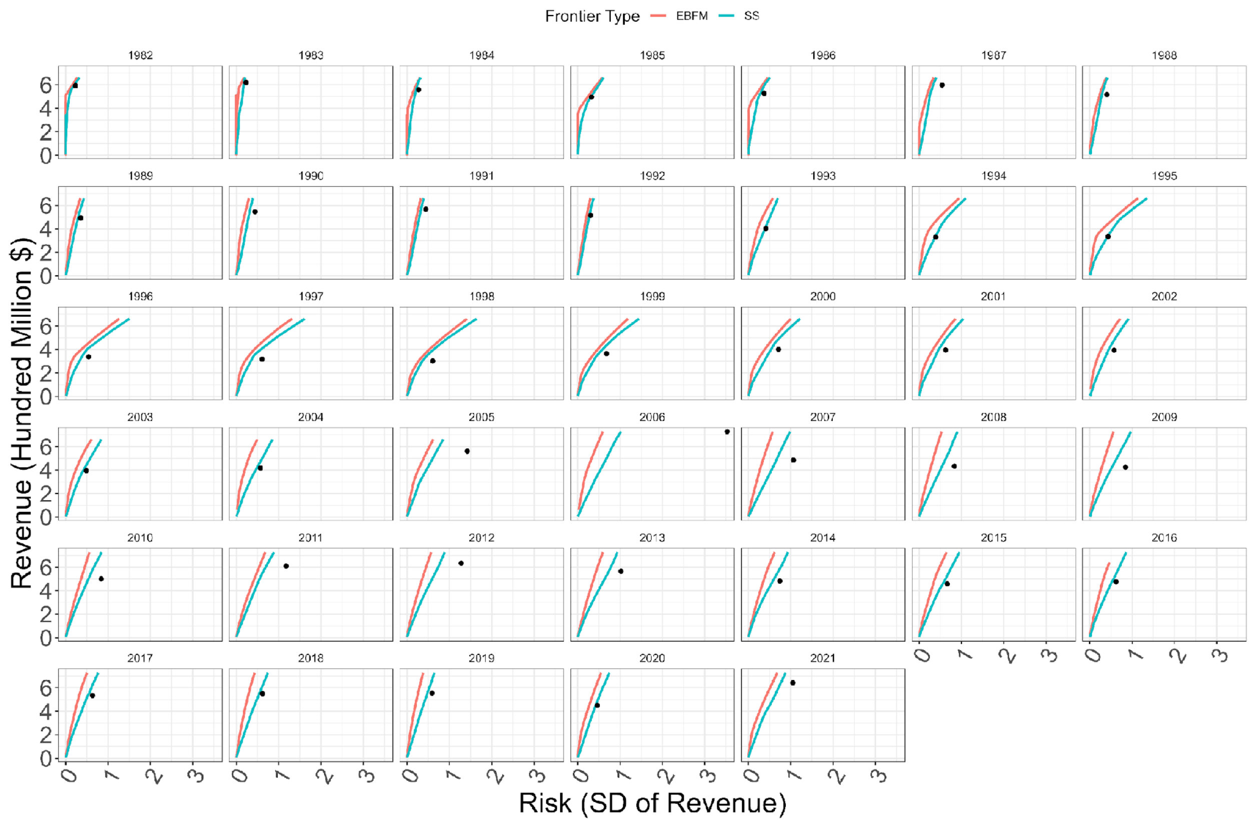

Figure 3. The realized revenue (dot) and multispecies-based fishery management (EBFM, red line) and single species management (SS, blue line) efficient frontiers for each year of the timeseries for New England. The vertical axis depicts the expected revenue (in 2021 dollars) and the horizontal axis depicts 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. 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 peak resulted from a spike in herring prices, driven by a change in perception of stock size, a decrease in allowable catch, and a demand for herring bait. These "Jin-style" (Jin et al. 2016) plots are from Brewster et al. 2025.

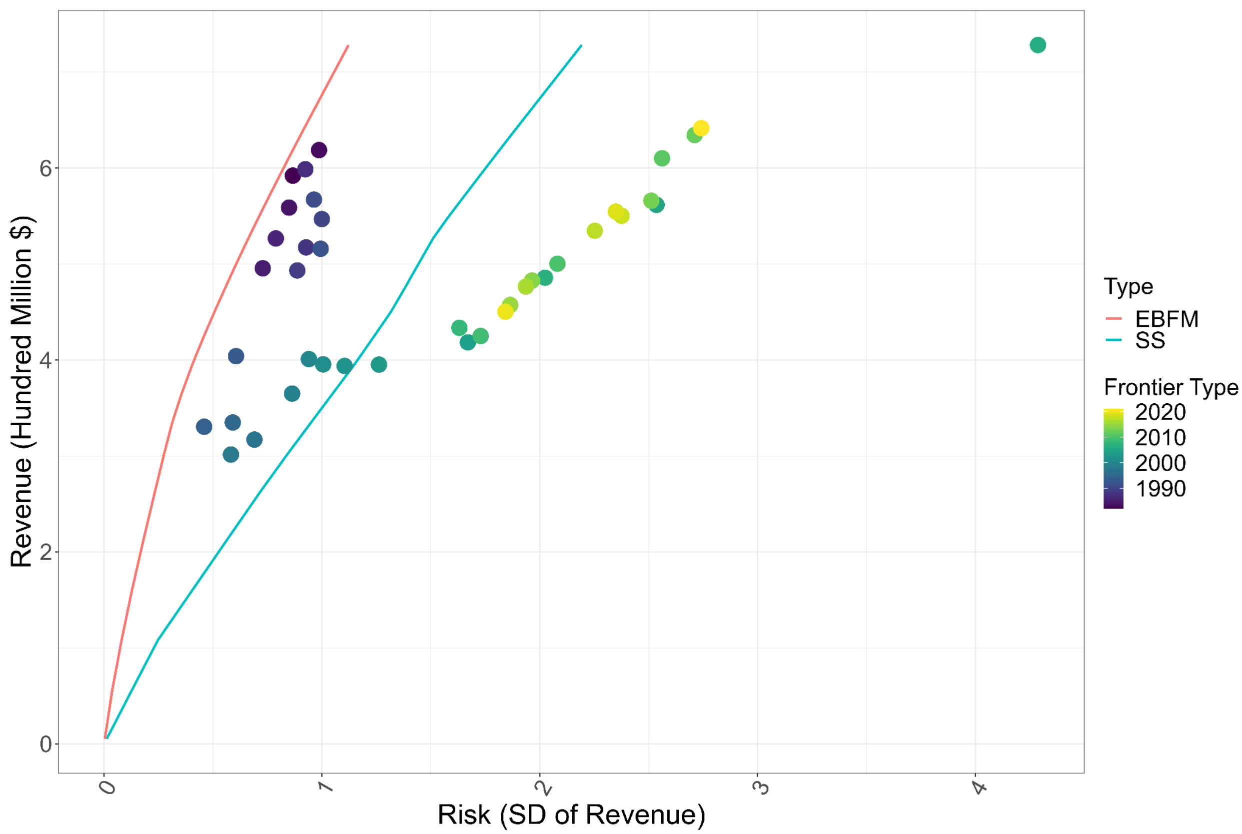

Figure 5. The snapshot (Sanchirico) style plot is a static plot and a simpler visualization. The risk associated with each year of observed revenue (colored dots) is calculated using the covariance matrix for the full time period, matching that which is used to generate the frontier. To make each frontier more applicable when plotted with the observed revenues, the time series could be broken into shorter stanzas. From Brewster et al. 2025.

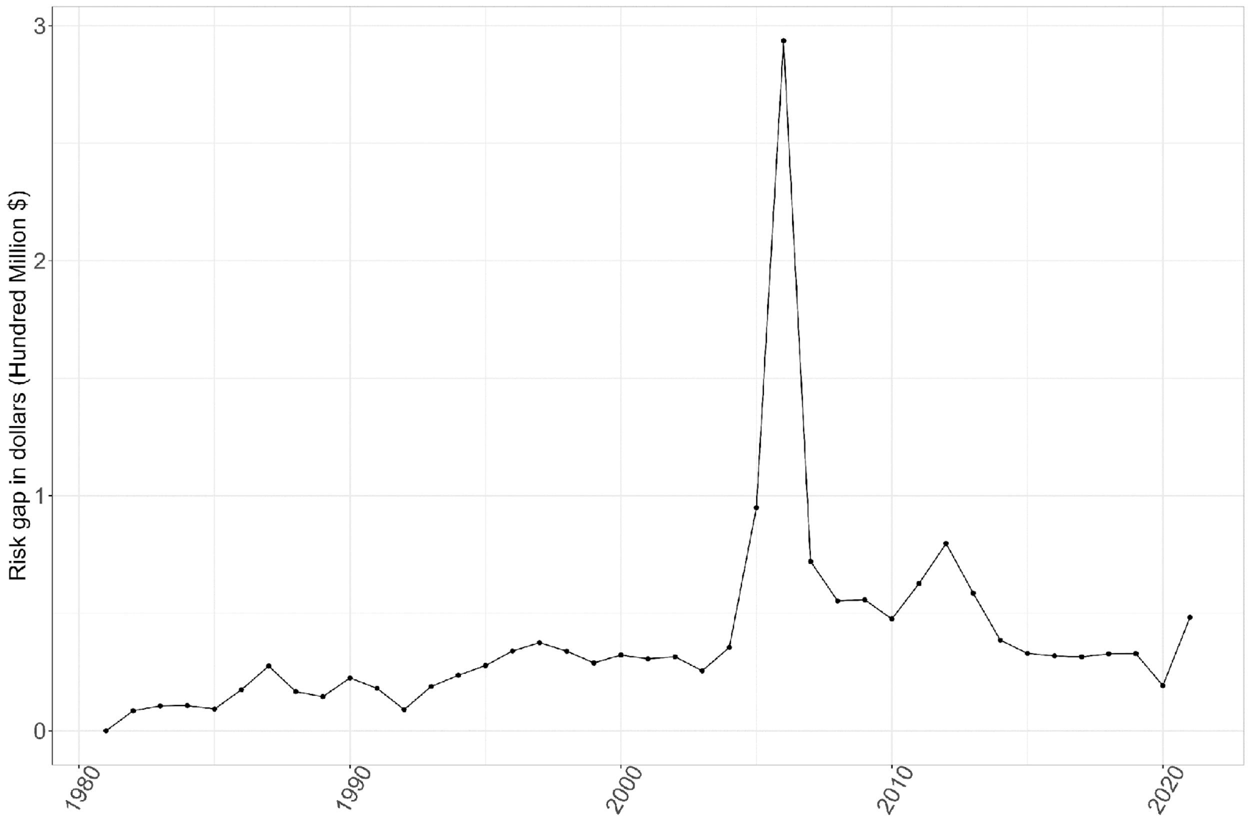

Figure 6. The risk gap is the difference in risk between the realized revenue and the equivalent point for the same revenue on the portfolio curve (i.e., RG2 on Figure 7). It is evident at the end of the timeseries in 2021, almost 50 million dollars worth of risk were taken than were necessary if the portfolio approach had been used. From Brewster et al. 2025.