Evaluating the conservation and economic performance of fisheries quota baskets: a Belizean fisheries case study

Mauricio Collado, Christopher Free, Erin O’Reilly, Steve Gaines

Executive summary

Quota baskets, which manage groups of species with similar traits using a single catch or effort limit, represent a promising approach for managing data-limited multi-species fisheries. Single-species assessment and management approaches are data-intensive and are simply not applicable in most fisheries contexts. Furthermore, even in data-rich contexts, rigid single-species approaches sacrifice the economic and nutritional benefits of multi-species fisheries when they require the conservation of “weak” stocks, i.e., stocks with lower productivity and/or higher vulnerability than the primary target stocks. Well-designed quota baskets may be able to balance conservation and socioeconomic objectives for data-limited species. However, a key challenge to implementing effective quota baskets is the lack of tools for validating the expected performance of proposed quota baskets and the lack of guidance for deriving catch or effort limits that achieve fisheries objectives, especially when data is limited.

In this project, we develop a flexible method of evaluating the effectiveness of proposed quota baskets and use this approach to provide guidance on how to set effective catch limits. We evaluate quota baskets proposed for the management of marine fisheries in Belize as a case study. We leverage a bioeconomic model developed by Collado et al. (2021) that incorporates the ability of fishers to switch gears and target different fisheries when confronted with quota basket management. Importantly, the model is parameterized using data from publicly available global-scale datasets and meta-analyses, which allows for it to be implemented in nearly any setting. We measure the performance of the proposed quota baskets in terms of their ability to keep the biomass of all species above a B_{MSY} management target (conservation performance) and their ability to maximize multi-species profits (economic performance). In this framework, a high-performing quota basket would achieve a high proportion of the cumulative single-species harvest without compromising the conservation status of any one species in the basket.

We evaluated the performance of 10 of 13 quota baskets proposed to manage 48 marine fish species in Belize. Two baskets were excluded because they contained only one species (Baskets 11 and 12), and one basket was excluded because it lacked the species-specific information required for evaluation (Basket 6). Of the ten evaluated baskets, two were deemed highly functional, in that they could be fished above 65% of the cumulative single-species MSY of constituent species and still keep the constituent species above the B_{MSY} management target: (a) Basket 5 - forereef/handline and (b) Basket 8 - pelagic/migratory handline. Two baskets were deemed non-functional, in that they must be fished below 30% of the cumulative single-species MSY to keep all species above the B_{MSY} management target: (a) Basket 1 - pelagic/migratory and (b) Basket 9 - large groupers. The remaining six baskets were deemed moderately functional, in that they can only be fished between 30%-65% of the cumulative single-species

MSY to maintain all species above the B_{MSY} management target. Overall, baskets containing species that are more similar in their level of vulnerability – a metric that combines both their productivity and their catchability – perform better than baskets with higher variability in vulnerability among constituent species. We provide recommendations for how to split baskets, if possible, to maintain conservation benefits with higher economic yields.

This study provides tactical insights into the likely performance of Belize's proposed quota baskets and into the scale of the basket-wide catch limit required to meet conservation objectives (i.e., keep the biomass of all species above the B_{MSY} management target). With reliable catch time series, reasonable estimates of MSY can be generated for data-limited species using catch-only methods such as Depletion-Based Stock Reduction Analysis (DB-SRA), Depletion Corrected Average Catch (DCAC), or CMSY. Although these methods are not useful in predicting stock status, they are useful in generating reasonable estimates of MSY, especially when expert knowledge of stock status is available. The study also provides a transferable and flexible tool for evaluating the performance of quota baskets in other fisheries worldwide. We show how the parameters required for the model can be derived from publicly available data sources. Automating this process could empower a wider community of users to evaluate the performance of quota baskets in their fishery systems.

1. Introduction

Quota baskets, which manage groups of species with similar traits using a single catch or effort limit (Sanchirico et al., 2006), represent a promising approach for managing data-limited multi-species fisheries (Collado et al., 2021; Karr et al., 2021). Single-species assessment and management approaches are data-intensive and are simply not applicable in most fisheries contexts. Furthermore, even in data-rich contexts, rigid single-species approaches sacrifice the economic and nutritional benefits of multi-species fisheries when they require the conservation of "weak" stocks, i.e., stocks with lower productivity and/or higher vulnerability than the primary target stocks. Well-designed quota baskets may be able to balance conservation and socioeconomic objectives for data-limited species. However, a key challenge to implementing effective quota baskets is the lack of tools for validating the expected performance of proposed quota baskets and the lack of guidance for deriving catch or effort limits that achieve fisheries objectives, especially when data is limited.

In this project, we develop a flexible method of evaluating the effectiveness of proposed quota baskets and use this approach to provide guidance on how to set effective catch limits. We evaluate quota baskets proposed for the management of marine fisheries in Belize as a case study. We leverage a bioeconomic model developed by Collado et al. (2021) that incorporates the ability of fishers to switch gears and target fisheries when confronted with quota basket management. Importantly, the model is parameterized using data from publicly available global-scale datasets and meta-analyses, which allows for it to be implemented in nearly any setting. We measure the performance of the proposed quota baskets in terms of its ability to keep all species above a B_{MSY} management target (conservation performance) and its ability to maximize multi-species profits (economic performance). A high-performing quota basket would be able to achieve a high proportion of the cumulative single-species harvest without compromising the conservation status of any one species in the basket.

2. Methods

2.1 The model

The Collado et al. (2021) model employs a myopic approach to a Gordon-Schaeffer bioeconomic model to identify fishermen's criteria for allocating efforts across fishing gears and quota baskets in response to established harvest limits. Briefly, the population dynamics of evaluated species follow logistic growth (Schaefer production model) (Schaefer, 1954), and the fleet dynamics are governed by profit optimization given population dynamics, gear selectivity, management, and prices. See Collado et al. (2021) and **Appendix B** for details on the modeling approach. All data and code are available on GitHub here: https://github.com/MauricioCollado/belize_basket_edf.git

2.2 The input parameters

The model can be parameterized for any fishery in the world using only the following data: (1) time series of species-specific catches; (2) expert knowledge of current species-specific fisheries status; and (3) current species-specific prices. Model parameters are derived from these data types using the following methods (see **Appendix C** for more details):

- **Current status:** Estimates of current status were based on expert knowledge. For Belize, these were derived from UNCTAD (2022), where healthy, moderate, and unhealthy statuses are assumed to correspond to 60% (1.2 B/B_{MSY}), 40% (0.8 B/B_{MSY}), and 20% (0.4 B/B_{MSY}) of unfished biomass, respectively.
- **Intrinsic growth rate (r):** Intrinsic growth rate (r) values were estimated using the *FishLife* R package (Thorson et al., 2023), which employs a meta-analysis of FishBase life history parameters (Froese & Pauly, 2023) to predict the intrinsic growth rate of any finfish species in the world. For other studies, invertebrate intrinsic growth rates can be derived from FishBase (Froese & Pauly, 2023). Intrinsic growth rates for species not included in either FishLife or FishBase could be estimated using CMSY, described below.
- **Carrying capacity (K), for stocks with catch time series:** Estimates of carrying capacity (K) for stocks with catch time series were derived using the CMSY catch-only stock assessment approach (Froese et al., 2017) as implemented in the *datalimited2* R package (Free, 2018). The results are conditioned on the status and intrinsic growth rate values derived above (i.e., narrow priors are set for these parameters using the estimates derived above). Although CMSY does not provide accurate estimates of stock status (Free et al., 2020; Ovando et al., 2022), it can provide useful estimates of carrying capacity and maximum sustainable yield (MSY) when expert opinion of stock status is assumed to be reliable.
- **Carrying capacity (K), for stocks without catch time series:** We cannot use CMSY to estimate carrying capacity for stocks without catch time series. Instead, because

ecological theory predicts that carrying capacity is inversely proportional to growth rate (Froese et al., 2017), we predicted carrying capacity as a function of growth rate using a linear model fit to the available carrying capacity and growth rate estimates.

- **Gear-specific catchabilities:** Gear-specific catchabilities were derived as values relative to a reference catchability value using gear-specific catch time series. The reference value was set to an arbitrarily low value, given that the units of effort in the model are also arbitrary.
- **Ex-vessel price:** The ex-vessel price (price per metric ton) was derived from the catch and ex-vessel revenue times series from the Sea Around Us Project database (Pauly, 2007).

We estimate these parameters for the 48 fish species included in the 13 quota baskets proposed for implementation in Belize (UNCTAD, 2022). These quota baskets are visualized in **Figure 1** below, where baskets were intended to group species with similar levels of vulnerability and depletion but were adjusted based on stakeholder feedback. Ultimately, we excluded three baskets from consideration in our analysis. Two baskets were excluded because they contained only one species (Baskets 11 and 12), and one basket was excluded because it lacked the species-specific information required for evaluation (Basket 6).

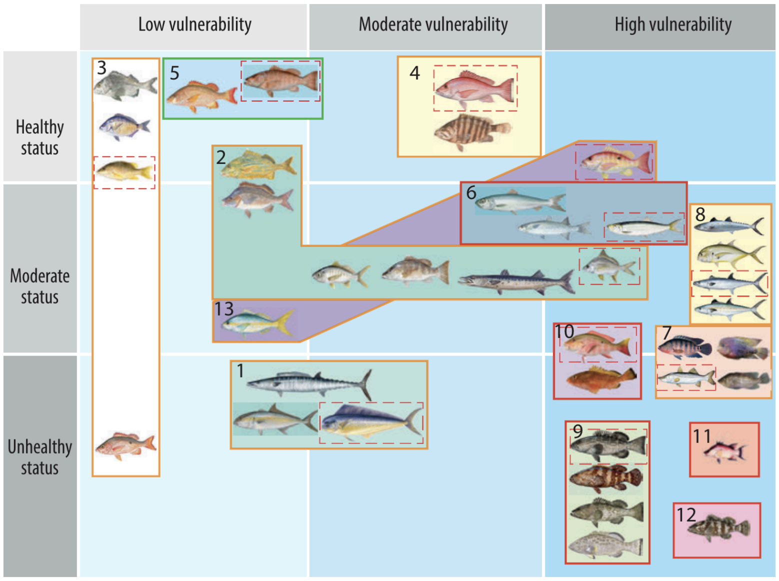
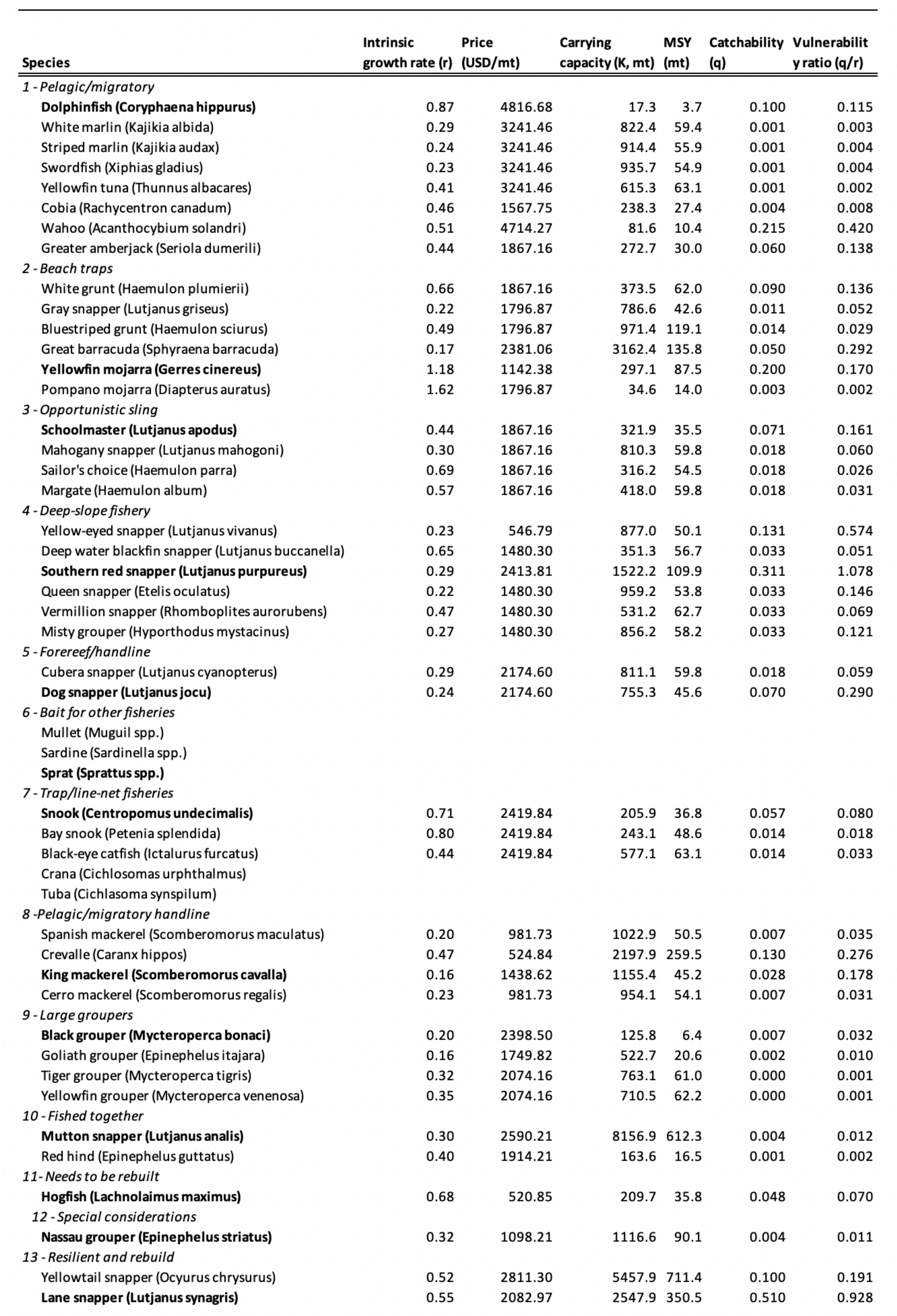


Figure 1. Baskets proposed for managing Belizean fisheries in UNCTAD (2022). Dashed red lines surround the proposed indicator species for each quota basket. Numbers indicate the basket number (see **Table 1** for details).

The resulting parameter estimates are shown in **Table 1** below.

Table 1. Species and parameters for the proposed Belizean quota baskets. Bolded species are the proposed indicator species. Basket numbers and names are from UNCTAD (2022).



Species	Intrinsic growth rate (r)	Price (USD/mt)	Carrying capacity (K, mt)	MSY (mt)	Catchability (q)	Vulnerability ratio (q/r)
1 - Pelagic/migratory						
Dolphinfish (Coryphaena hippurus)	0.87	4816.68	17.3	3.7	0.100	0.115
White marlin (Kajikia albida)	0.29	3241.46	822.4	59.4	0.001	0.003
Striped marlin (Kajikia audax)	0.24	3241.46	914.4	55.9	0.001	0.004
Swordfish (Xiphias gladius)	0.23	3241.46	935.7	54.9	0.001	0.004
Yellowfin tuna (Thunnus albacares)	0.41	3241.46	615.3	63.1	0.001	0.002
Cobia (Rachycentron canadum)	0.46	1567.75	238.3	27.4	0.004	0.008
Wahoo (Acanthocybium solandri)	0.51	4714.27	81.6	10.4	0.215	0.420
Greater amberjack (Seriola dumerili)	0.44	1867.16	272.7	30.0	0.060	0.138
2 - Beach traps						
White grunt (Haemulon plumierii)	0.66	1867.16	373.5	62.0	0.090	0.136
Gray snapper (Lutjanus griseus)	0.22	1796.87	786.6	42.6	0.011	0.052
Bluestriped grunt (Haemulon sciurus)	0.49	1796.87	971.4	119.1	0.014	0.029
Great barracuda (Sphyraena barracuda)	0.17	2381.06	3162.4	135.8	0.050	0.292
Yellowfin mojarra (Gerres cinereus)	1.18	1142.38	297.1	87.5	0.200	0.170
Pompano mojarra (Diapterus auratus)	1.62	1796.87	34.6	14.0	0.003	0.002
3 - Opportunistic sling						
Schoolmaster (Lutjanus apodus)	0.44	1867.16	321.9	35.5	0.071	0.161
Mahogany snapper (Lutjanus mahogoni)	0.30	1867.16	810.3	59.8	0.018	0.060
Sailor's choice (Haemulon parra)	0.69	1867.16	316.2	54.5	0.018	0.026
Margate (Haemulon album)	0.57	1867.16	418.0	59.8	0.018	0.031
4 - Deep-slope fishery						
Yellow-eyed snapper (Lutjanus vivanus)	0.23	546.79	877.0	50.1	0.131	0.574
Deep water blackfin snapper (Lutjanus buccanella)	0.65	1480.30	351.3	56.7	0.033	0.051
Southern red snapper (Lutjanus purpureus)	0.29	2413.81	1522.2	109.9	0.311	1.078
Queen snapper (Etelis oculatus)	0.22	1480.30	959.2	53.8	0.033	0.146
Vermillion snapper (Rhomboplites aurorubens)	0.47	1480.30	531.2	62.7	0.033	0.069
Misty grouper (Hyporthodus mystacinus)	0.27	1480.30	856.2	58.2	0.033	0.121
5 - Forereef/handline						
Cubera snapper (Lutjanus cyanopterus)	0.29	2174.60	811.1	59.8	0.018	0.059
Dog snapper (Lutjanus jocu)	0.24	2174.60	755.3	45.6	0.070	0.290
6 - Bait for other fisheries						
Mullet (Muguil spp.)						
Sardine (Sardinella spp.)						
Sprat (Sprattus spp.)						
7 - Trap/line-net fisheries						
Snook (Centropomus undecimalis)	0.71	2419.84	205.9	36.8	0.057	0.080
Bay snook (Petenia splendida)	0.80	2419.84	243.1	48.6	0.014	0.018
Black-eye catfish (Ictalurus furcatus)	0.44	2419.84	577.1	63.1	0.014	0.033
Crana (Cichlosomas urphthalmus)						
Tuba (Cichlasoma synspilum)						
8 -Pelagic/migratory handline						
Spanish mackerel (Scomberomorus maculatus)	0.20	981.73	1022.9	50.5	0.007	0.035
Crevalle (Caranx hippos)	0.47	524.84	2197.9	259.5	0.130	0.276
King mackerel (Scomberomorus cavalla)	0.16	1438.62	1155.4	45.2	0.028	0.178
Cerro mackerel (Scomberomorus regalis)	0.23	981.73	954.1	54.1	0.007	0.031
9 - Large groupers						
Black grouper (Mycteroperca bonaci)	0.20	2398.50	125.8	6.4	0.007	0.032
Goliath grouper (Epinephelus itajara)	0.16	1749.82	522.7	20.6	0.002	0.010
Tiger grouper (Mycteroperca tigris)	0.32	2074.16	763.1	61.0	0.000	0.001
Yellowfin grouper (Mycteroperca venenosa)	0.35	2074.16	710.5	62.2	0.000	0.001
10 - Fished together						
Mutton snapper (Lutjanus analis)	0.30	2590.21	8156.9	612.3	0.004	0.012
Red hind (Epinephelus guttatus)	0.40	1914.21	163.6	16.5	0.001	0.002
11- Needs to be rebuilt						
Hogfish (Lachnolaimus maximus)	0.68	520.85	209.7	35.8	0.048	0.070
12 - Special considerations						
Nassau grouper (Epinephelus striatus)	0.32	1098.21	1116.6	90.1	0.004	0.011
13 - Resilient and rebuild						
Yellowtail snapper (Ocyurus chrysurus)	0.52	2811.30	5457.9	711.4	0.100	0.191
Lane snapper (Lutjanus synagris)	0.55	2082.97	2547.9	350.5	0.510	0.928

2.3 Harvest policies and performance metrics

We evaluated the performance of each quota basket under harvest policies that set the basket-wide catch limit as a percentage of the cumulative maximum sustainable yield (MSYs) of the individual species included in the quota basket. If each species could be targeted individually (i.e., if the fishery were perfectly selective), then 100% of the cumulative MSYs would be the maximum amount of catch that could be derived from the species included in the basket. However, in a multi-species fishery that cannot selectively avoid species, it is unlikely that this level of yield could be sustainably taken without overfishing the weakest of the stocks. Thus, we evaluate the performance of percentages of this maximum value from 1 to 100%. This harvest policy design is useful because it provides an easy to conceptualize metric of how conservative a policy must be to achieve conservation goals (i.e., 10% of cumulative MSY is a very conservative policy, whereas 90% of cumulative MSY is a very efficient policy) and because the MSY of species can be reasonably estimated in catch-only settings (Wetzel & Punt, 2011).

We measured the performance of each harvest policy in terms of (1) the cumulative 30-year profits generated by the policy (economic performance) and (2) the population status of each species in the basket in the 30th year. We measure population status as the biomass relative to the B_{MSY} management target (B/B_{MSY}), where values greater than 1.0 indicate well-managed stocks and values less than 1.0 indicate overfished stocks. In this framework, the best policy for each basket is the policy that maximizes profits while keeping all species above the B_{MSY} management target. If the basket is well-designed – i.e., the stocks in the basket all have a similar vulnerability to fishing – then conservation goals could be met while taking a large percentage of the cumulative maximum sustainable yield. However, if the basket is poorly designed – i.e., the stocks in the basket have different vulnerabilities to fishing – the catch limit will have to be conservative to protect the most limiting stock. We measure the similarity of the stocks within each quota basket by measuring the coefficient of variation in their vulnerability, which is calculated as the ratio between productivity (r) and catchability (q).

We qualitatively judge the performance of the basket using the following criteria:

- **Exceptionally functional baskets** can be fished above 90% of the cumulative MSY of the constituent species and keep all species above the B_{MSY} management target;
- **Highly functional baskets** can be fished above 65% of the cumulative MSY of the constituent species and keep all species above the B_{MSY} management target;
- **Moderately functional baskets** can only be fished between 30%-65% of the cumulative MSY and maintain all species above the B_{MSY} management target
- **Non-functional baskets** must be fished below 30% of the cumulative MSY of the constituent species to keep all species above the B_{MSY} management target.

Ultimately, we did not find evidence for any exceptionally functional quota baskets.

3. Results

3.1 Example results

In Appendix A, we visualize the results of the analysis of each quota basket using the same two figures. We provide the results for Basket 9 (Large groupers) here.

The first figure illustrates the time series of stock status, exploitation rate, and revenues for each of the species in the basket under the hundred different harvest policies (1-100% of the cumulative MSY of all species in the basket, in increments of 1%) (**Figure 2**). Stock status is reported as the biomass relative to the B_{MSY} management target (B/B_{MSY}), where values greater than 1.0 indicate a healthy stock and values less than 1.0 indicate an overfished stock. Exploitation rate is represented as the catch over the biomass such that a value of zero indicates no harvest and a value of one marks extinction of the stock (i.e., all biomass taken as harvest). The revenues of each species are calculated as the catch times the static price; as a result, revenues are proportional to harvest. Although we calculate basket-wide profits, we do not calculate the profits associated with a single species, since the species have shared costs.

In the Basket 9 example figure, you will see that all four stocks begin overexploited (B/BMSY < 1.0). Tiger grouper and yellowfin grouper rebuild under all harvest policies but black grouper and goliath grouper require more conservative harvest policies to rebuild.

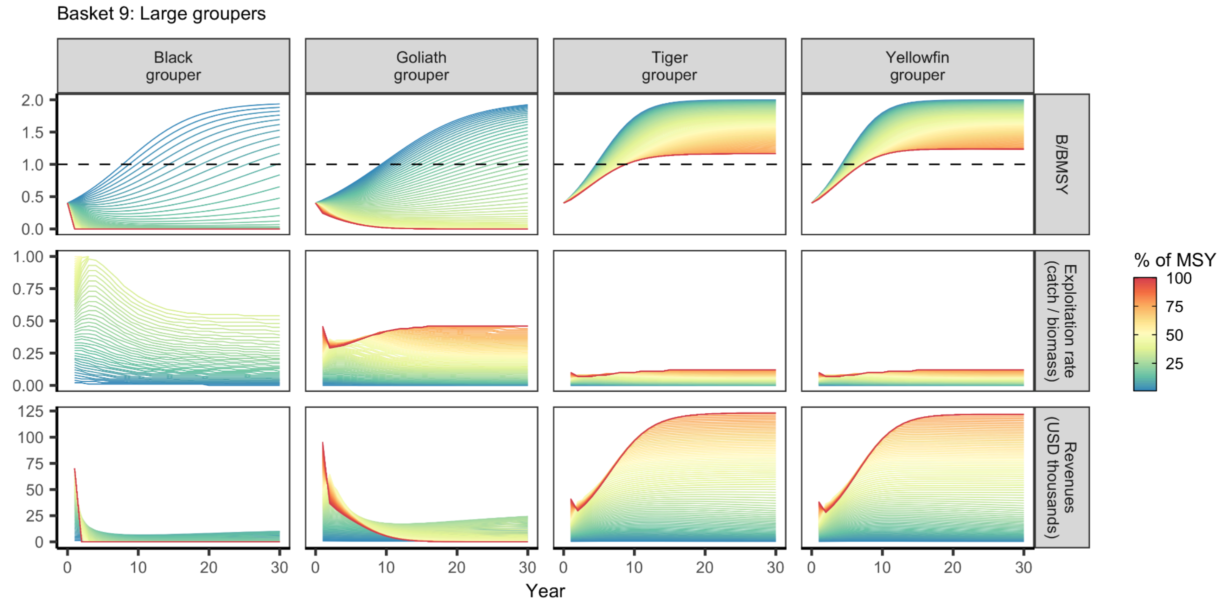


Figure 2. Population trajectories for species managed in Basket 9 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

The second figure illustrates tradeoffs in conservation and economic performance by harvest policy (**Figure 3**). The x-axis, which captures the conservation performance, indicates the status (B/B_{MSY}) of each species in the basket in the 30th and final year of the projection under each harvest policy. The y-axis, which captures the economic performance, represents the total basket-wide profits associated with the harvest policy. The figure can thus be used to identify the harvest policy that is able to maximize economic profits while keeping an individual species, a set of species, or all of the species above the B_{MSY} management target. For each species, the harvest policy that maximizes profits while maintaining the long-term conservation of the species is labeled. The smallest of these values thus represents the harvest policy required to maintain all species above the B_{MSY} management target and we refer to the species with the smallest value as being "most limiting". The figure could also be used to weigh the economic benefits of being willing to sacrifice the conservation of the most limiting species. In many cases, if managers were willing to overfish the limiting species, higher profits could be maintained while maintaining the conservation of the other species in the basket.

In the Basket 9 example figure, you can see that basket-wide profits would be maximized if it were acceptable to fish goliath grouper and black grouper to extinction. However, to maintain all species above the B_{MSY} management target, the catch limits would need to be less than 11% of the cumulative single species MSY, as this is the maximum harvest intensity that black grouper, the most limiting species, can withstand and still exceed the B_{MSY} management target. This basket provides an interesting example because it shows how efficiency could be increased if yellowfin and tiger grouper could be split into a separate basket from goliath and black grouper.

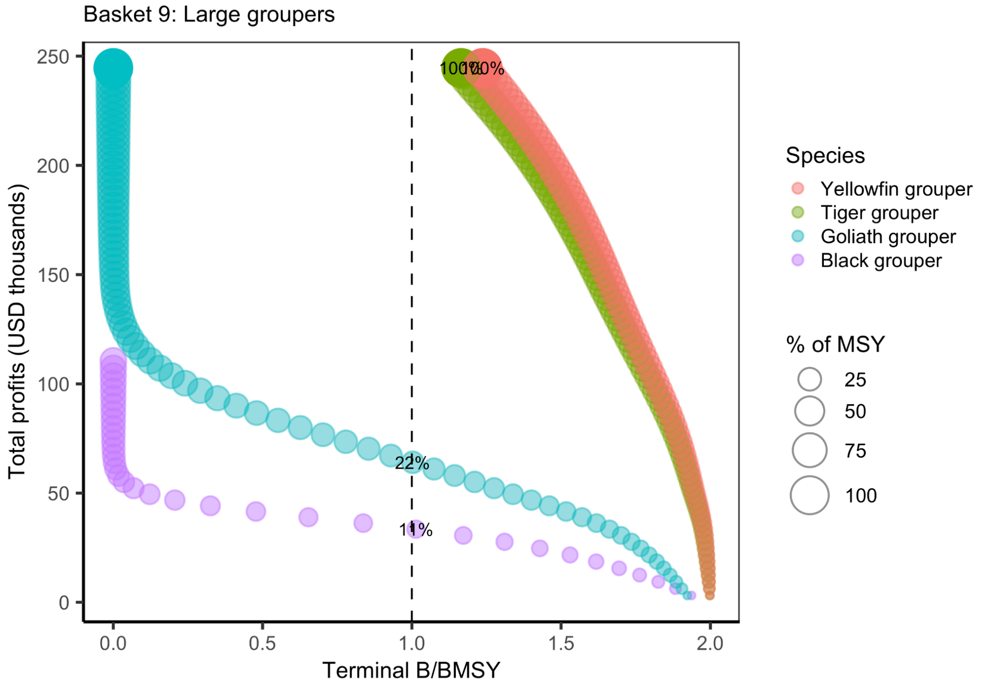


Figure 3. Tradeoffs between stock status and profits for species managed in Basket 9 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

3.2 Quota basket performance

Of the ten evaluated baskets, two were deemed highly functional, in that they could be fished above 65% of the cumulative single-species MSY of constituent species and still maintain all constituent species above the B_{MSY} management target: (a) Basket 5 - forereef/handline and (b) Basket 8 - pelagic/migratory handline. Two baskets were deemed non-functional, in that they must be fished below 30% of the cumulative single-species MSY to keep all species above the B_{MSY} management target: (a) Basket 1 - pelagic/migratory and (b) Basket 9 - large groupers. The remaining six baskets were deemed moderately functional, in that they can only be fished between 30%-65% of the cumulative single-species MSY to maintain all species above the B_{MSY} management target.

The following table summarizes the performance of the ten evaluated quota baskets and provides recommendations about (1) how they might be subdivided to increase economic efficiency and (2) the magnitude of the catch limit that would maximize economic returns while allowing all stocks in the basket to remain above the B_{MSY} management target.

Table 2. Summary of performance for the proposed Belizean quota baskets.

Basket ("id - name")	**Summary**
1 - Pelagic/migratory	This is not a functional quota basket. The quota must be quite conservative (<8% of cumulative MSY) to keep wahoo above the B_{MSY} management target. Wahoo, greater amberjack, and dolphinfish exhibit similarly high vulnerability and would be better managed in a separate basket. Tuna, marlin, and swordfish exhibit similarly low vulnerability and would also be better managed in their own basket. Cobia exhibits intermediate vulnerability and could be better managed in its own basket **(Figures S1 & S2)**.
2 - Beach traps	This is a moderately functional quota basket. The quota must be somewhat conservative (~58% of cumulative MSY) to keep the stocks managed within the basket above the B_{MSY} management target. The basket would be even more functional if great barracuda, the most limiting of the six species, could be targeted in a separate basket **(Figures S3 & S4)**.
3 - Opportunistic sling	This is a moderately functional quota basket. The quota must be somewhat conservative (~50% of cumulative MSY) to keep the stocks managed within the basket above the B_{MSY} management target. The basket would be even more functional if schoolmaster, the most limiting of the six

	species, could be targeted in a separate basket **(Figures S5 & S6)**.
4 - Deep slope fishery	This is a moderately functional quota basket. The quota must be somewhat conservative (~48% of cumulative MSY) to keep the stocks managed within the basket above the B_{MSY} management target. Southern red snapper is most limiting. If southern red snapper and yellow-eyed snapper could be targeted within a separate basket, the separated baskets would be even more efficient **(Figures S7 & S8)**.
5 - Forereef/handline	This is a highly functional quota basket. The quota can be quite high (~68% of cumulative MSY) and still keep the stocks managed within the basket above the B_{MSY} management target. Dog snapper is the more limiting of the two species **(Figures S9 & S10)**.
6 - Bait for other fisheries	*Not evaluated because of lack of species-specific data for this basket*
7 - Trap/line/net fisheries	This is a moderately functional quota basket. The quota must be somewhat conservative (~40% of cumulative MSY) to keep the stocks managed within the basket above the B_{MSY} management target. Snook is the more limiting of the three species, though not by much. The conservatism arises from the high current depletion of the stocks **(Figures S11 & S12)**.
8 - Pelagic/migratory handline	This is a highly functional quota basket. The quota can be quite high (~73% of cumulative MSY) and keep the stocks managed within the basket above the B_{MSY} management target. Crevalle and king mackerel exhibit higher vulnerability than cerro and Spanish mackerel, and dividing these species into separate baskets, if possible, would be even more functional **(Figures S13 & S14)**.
9 - Large groupers	This is not a functional quota basket. The quota must be highly conservative (~11% of cumulative MSY) to keep the stocks managed within the basket above the B_{MSY} management target. Goliath and black grouper exhibit much higher vulnerability than yellowfin and tiger grouper and, if possible, should be managed in a separate basket. A yellowing/tiger grouper basket would be extremely functional, and a goliath/black grouper basket would be moderately to highly functional **(Figures S15 & S16)**.

10 - Fished together	This is a moderately functional quota basket. The quota must be somewhat conservative (~62% of cumulative MSY) to keep the stocks managed within the basket above the B_{MSY} management target. Mutton snapper is the more limiting of the two species **(Figures S17 & S18)**.
11 - Needs to be rebuilt	*Not evaluated because there is only species in the basket*
12 - Special consideration	*Not evaluated because there is only species in the basket*
13 - Resilient and rebuild	This is a moderately functional quota basket. The quota must be somewhat conservative (~57% of cumulative MSY) to keep the stocks managed within the basket above the B_{MSY} management target. Lane snapper is the more limiting of the two species **(Figures S19 & S20)**.

3.3 Properties of a functional quota basket

In general, quota baskets perform best – i.e., they are able to maximize profits while achieving conservation goals – when the stocks managed in the baskets exhibit similar vulnerabilities. Stocks with more similar vulnerabilities, which is measured by their productivity (r, intrinsic growth rates) and catchability (q), can endure more similar harvest rates, which means that harvest rates do not have to be as conservatively reduced to protect the weaker of the stocks.

We illustrate this finding in **Figure 4**, which shows that for the 10 evaluated quota baskets, the baskets with differing vulnerabilities (high coefficient of variation between stocks) must be managed using more conservative harvest rates to meet conservation goals than stocks with more similar vulnerabilities (low coefficient of variation between stocks). This interaction is also impacted by initial stock status, as highly depleted stocks must have conservative harvest rates to rebuild, whereas less depleted stocks can endure higher harvest rates.

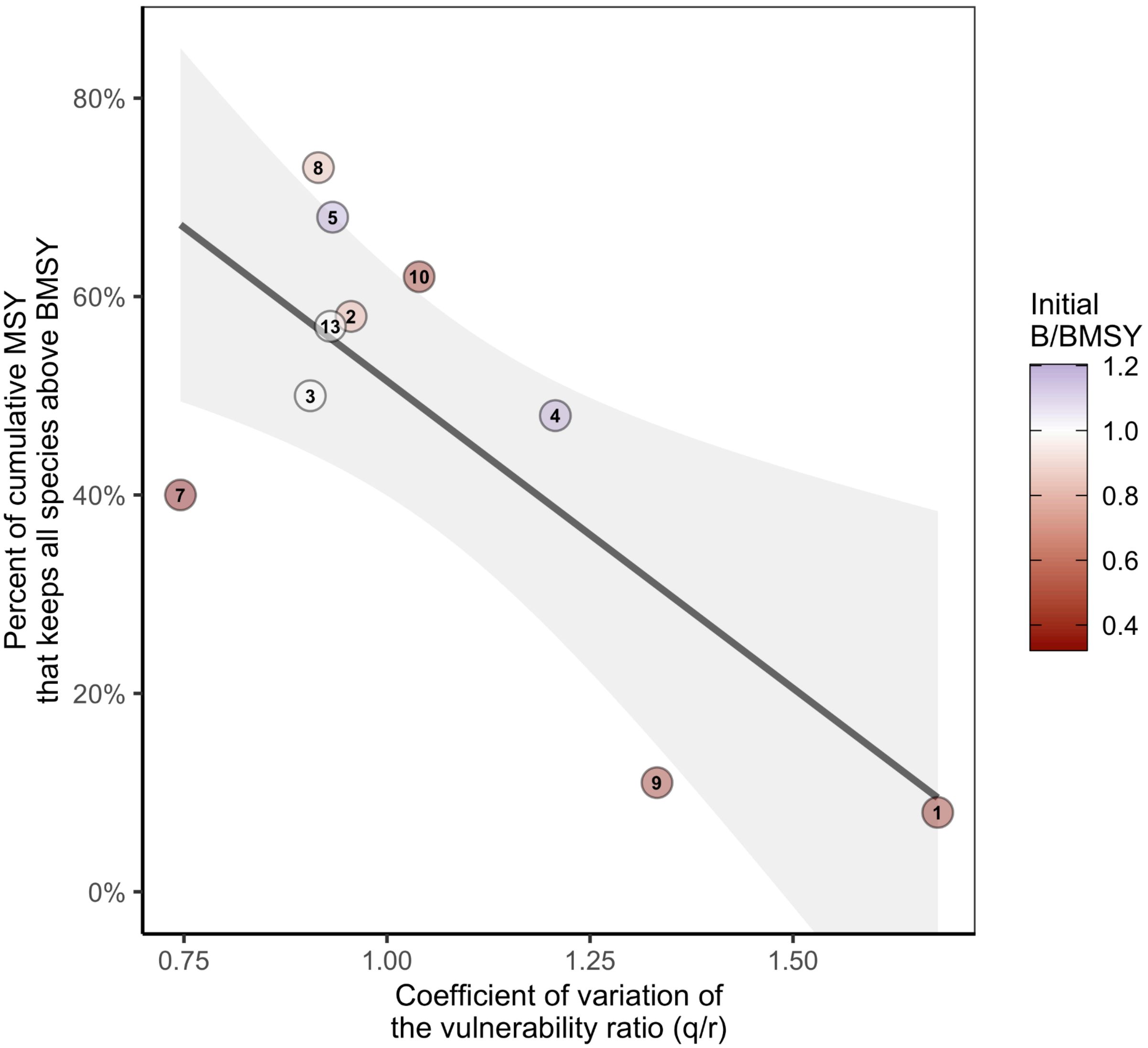


Figure 4. The relationship between the maximum percentage of the cumulative MSY that maintains all species in a basket above the B_{MSY} management target and the coefficient of variation in the vulnerability ratio (q/r) of species managed in the basket. Point color indicates the average status (B/B_{MSY}) of stocks in the basket, and points are numbered with the basket id. Line shows a linear regression fit to the data, and the gray shading indicates the 95% confidence interval.

4. Conclusions

This study provides tactical insights into the likely performance of Belize's proposed quota baskets and into the scale of the basket-wide catch limit required to meet conservation objectives (i.e., keep all species above the B_{MSY} management target). With reliable catch time series, reasonable estimates of MSY can be generated for data-limited species using catch-only methods such as Depletion-Based Stock Reduction Analysis (DB-SRA) (Dick & MacCall, 2011), Depletion Corrected Average Catch (DCAC) (MacCall, 2009), or CMSY (Froese et al., 2017).

Although these methods are not useful in predicting stock status (Free et al., 2020; Ovando et al., 2022), they are useful in generating reasonable estimates of MSY, especially when expert knowledge of stock status is available (Wetzel & Punt, 2011). The study also provides a transferable and flexible tool for evaluating the performance of quota baskets in other fisheries worldwide. We show how the parameters required for the model can be derived from publicly available data sources. Automating this process could empower a wider community of users to evaluate the performance of quota baskets in their fishery systems.

There are several promising next steps for this research. First, the harvest policies we evaluate maintain the same catch year-after-year. While these policies ease the analysis burden on fisheries managers and provide fishers with predictability and stability, they forego potential yield when stocks recover above the B_{MSY} management target. A key next step is to explore methods for adjusting the basket limit up or down in response to an index of abundance tracked for an indicator species (e.g., (ICES, 2022; Wiedenmann et al., 2019)). This would allow the catch limit to increase in response to increasing abundance or to decrease when abundance declines due to environmental conditions or scientific uncertainty. Furthermore, it will be important to evaluate the resilience of quota baskets to climate change. If the impact of climate change is to largely introduce variability and the species in the quota basket exhibit different responses to climate change, then quota baskets may provide inherent social-ecological resilience. However, if climate change impacts are largely directional, species with negative responses could become increasingly limiting, necessitating the creation of new baskets.

Researching basket effectiveness under schemes such as tradable quotas or harvest taxes could be useful in dealing with uncertainty, including uncertainty introduced by climate change. These instruments have the potential to deal better with shocks (on intrinsic growth or stock measurement) and information asymmetry between managers and fishers. Expanding the current model to incorporate non-myopic management, monitoring costs, and social welfare is necessary in this context. Furthermore, additional work is needed to understand the impact of quota basket management on issues such as bycatch and discarding across coexisting fishing gears and baskets, multiple baskets managed by different managers, and predator-prey relationships. Lastly, the model requires more exploration in terms of demand and more complex cost structures including transition costs to switch technologies, time delays in shifting technologies, and economies of scope of catching multiple species.

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Appendix A. Detailed results

Basket 1

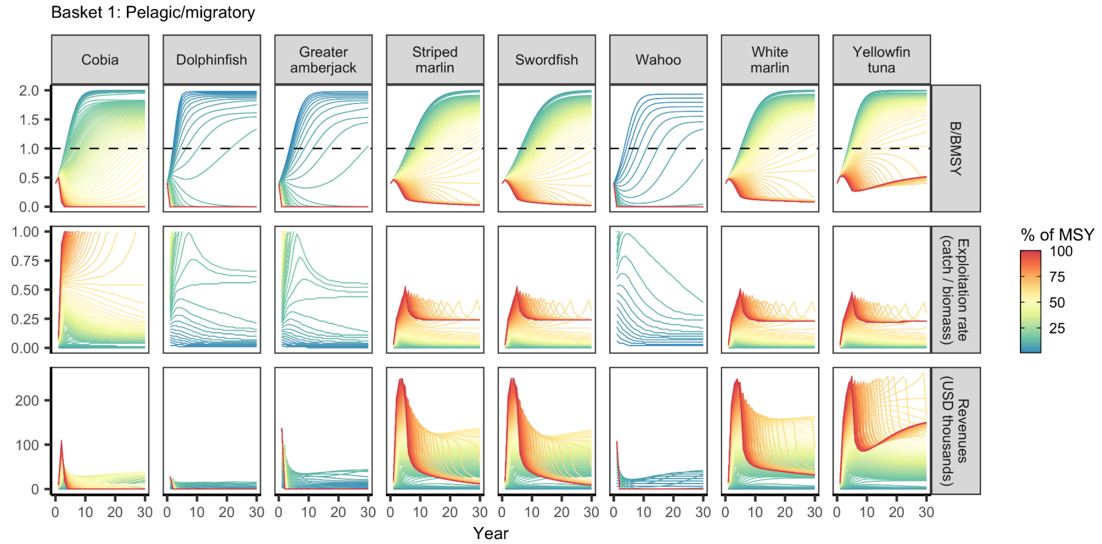

Figure S1. Population trajectories for species managed in Basket 1 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

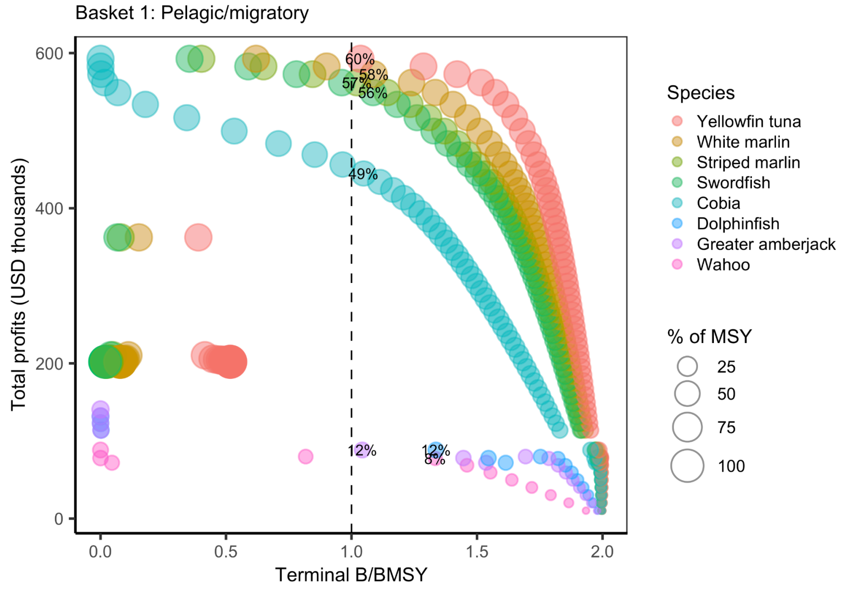

Figure S2. Tradeoffs between stock status and profits for species managed in Basket 1 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 2

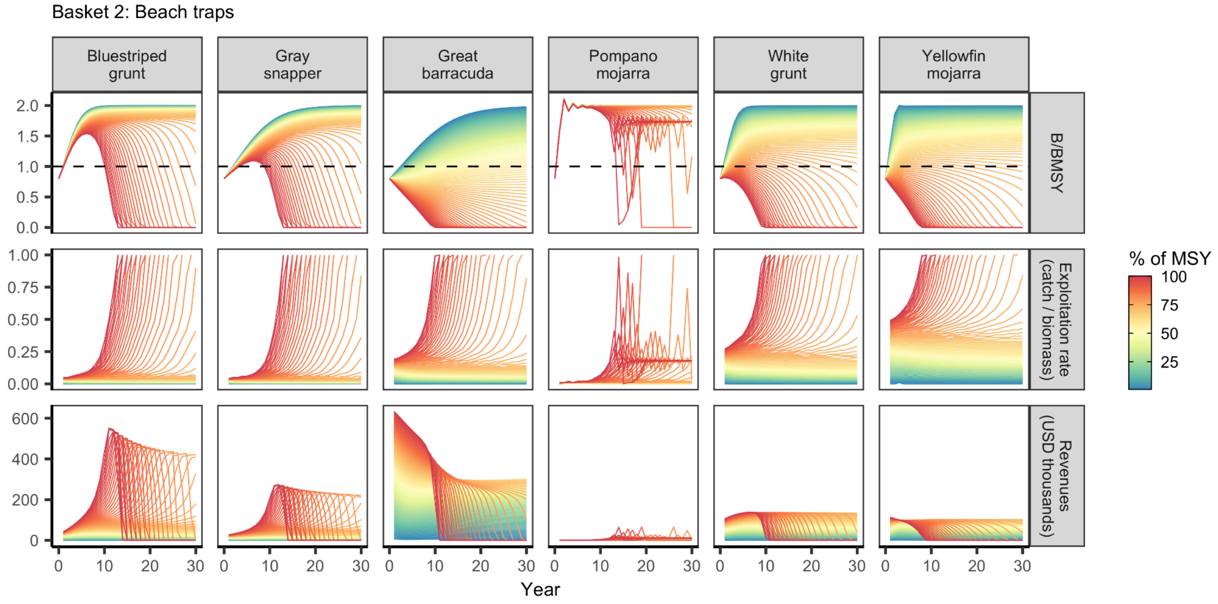

Figure S3. Population trajectories for species managed in Basket 2 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

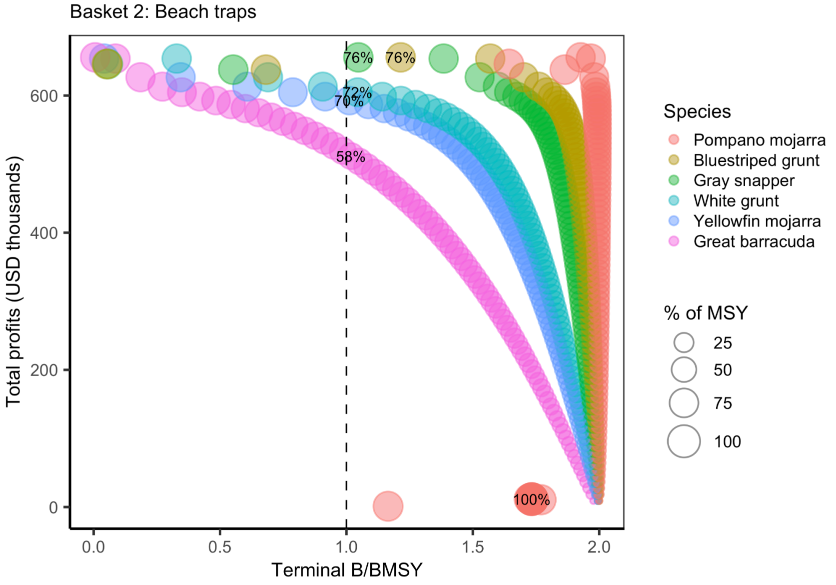

Figure S4. Tradeoffs between stock status and profits for species managed in Basket 2 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 3

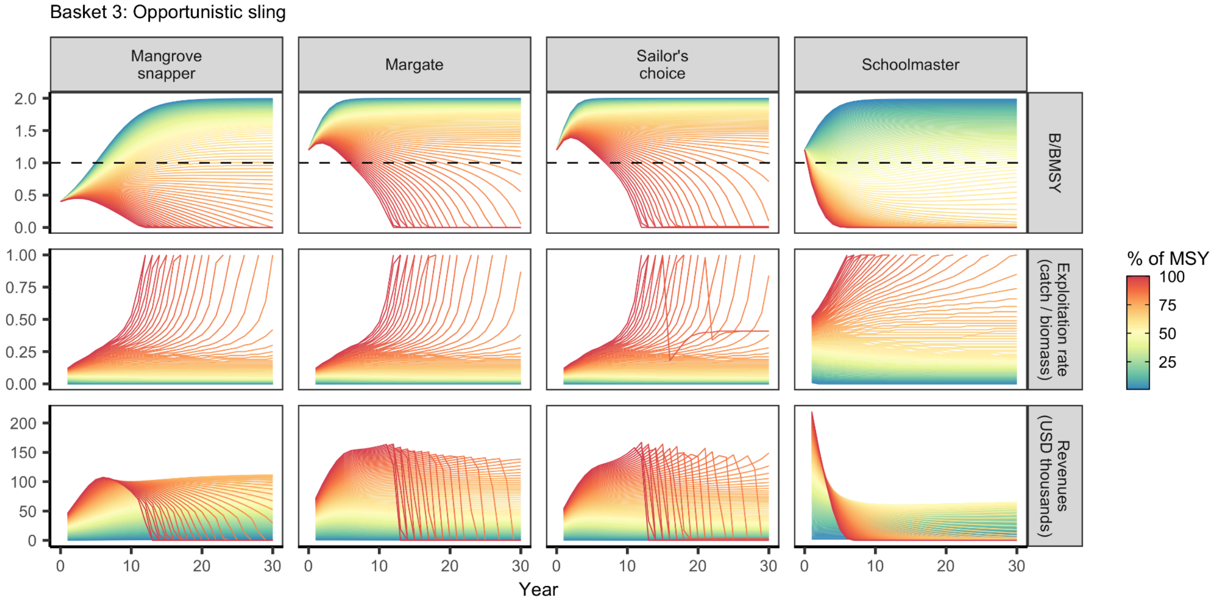

Figure S5. Population trajectories for species managed in Basket 3 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

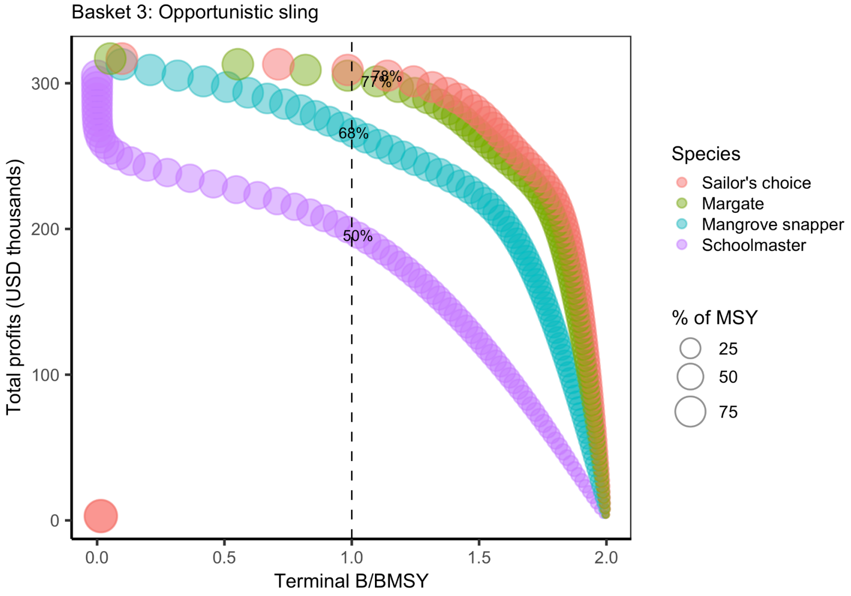

Figure S6. Tradeoffs between stock status and profits for species managed in Basket 3 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 4

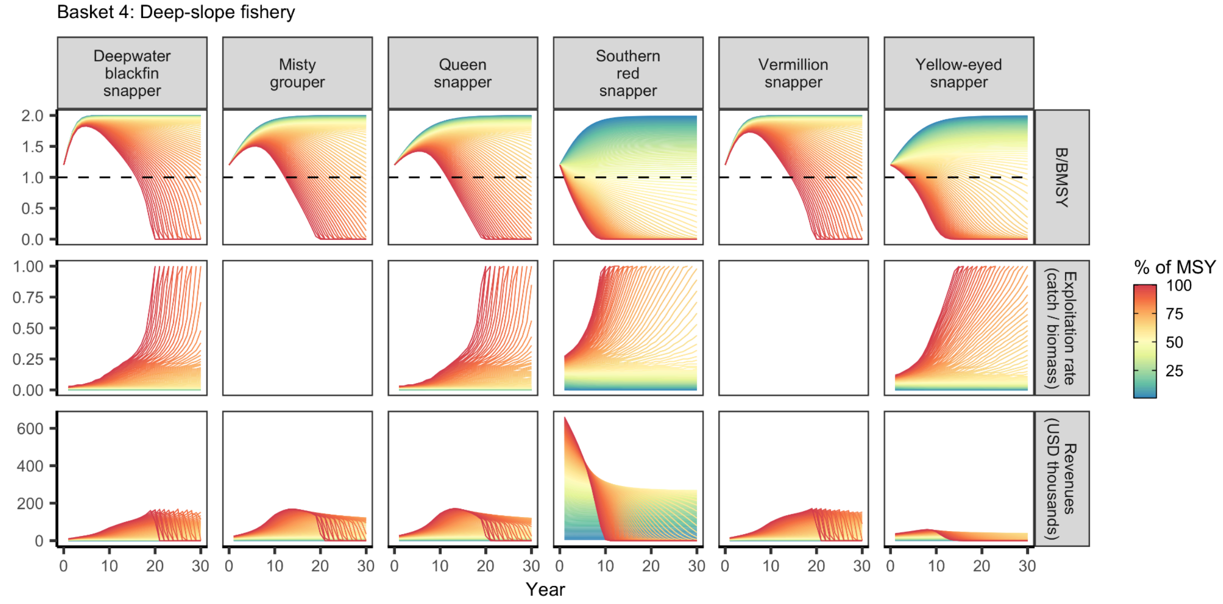

Figure S7. Population trajectories for species managed in Basket 4 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

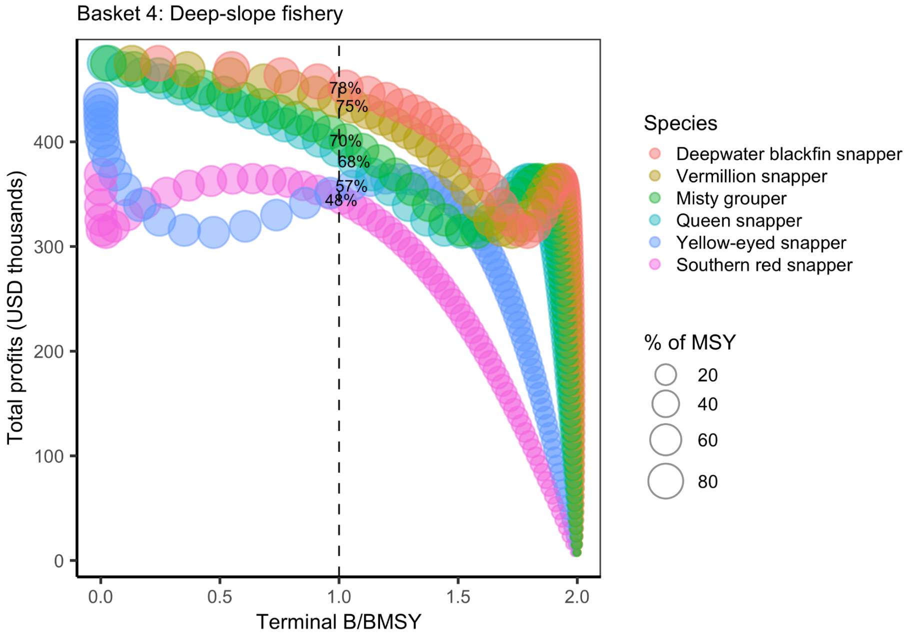

Figure S8. Tradeoffs between stock status and profits for species managed in Basket 4 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 5

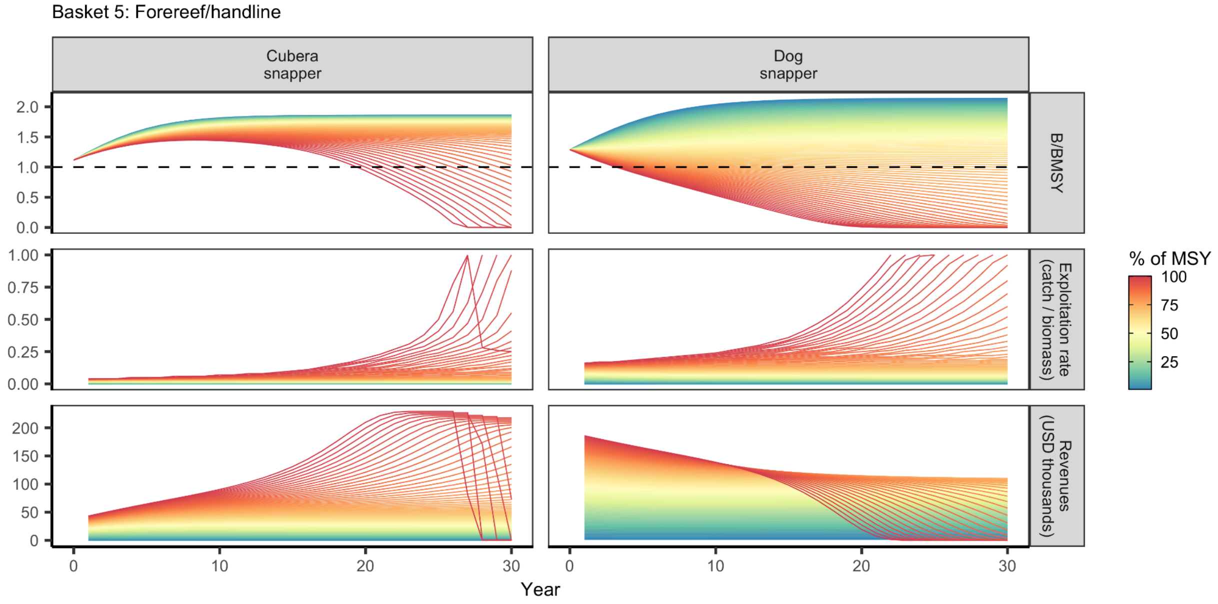

Figure S9. Population trajectories for species managed in Basket 5 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

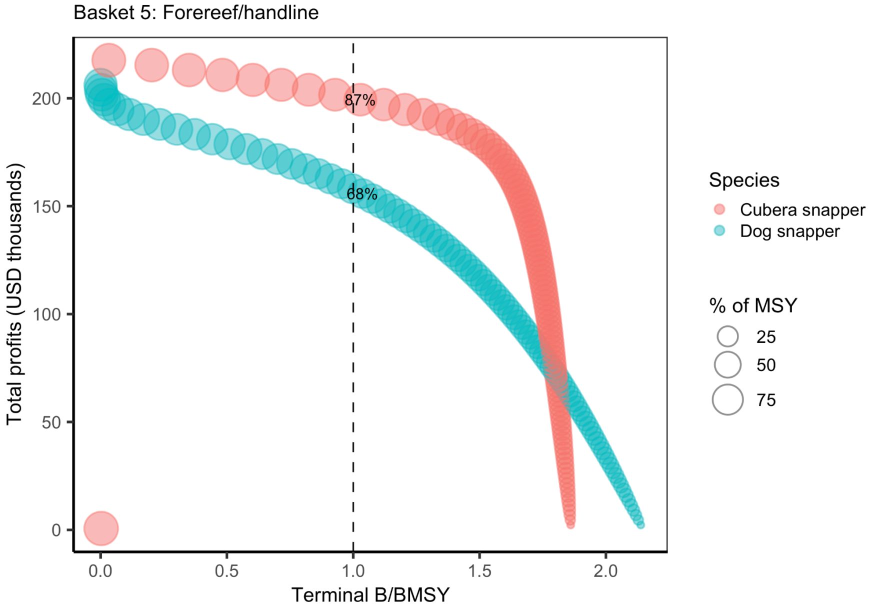

Figure S10. Tradeoffs between stock status and profits for species managed in Basket 5 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 7

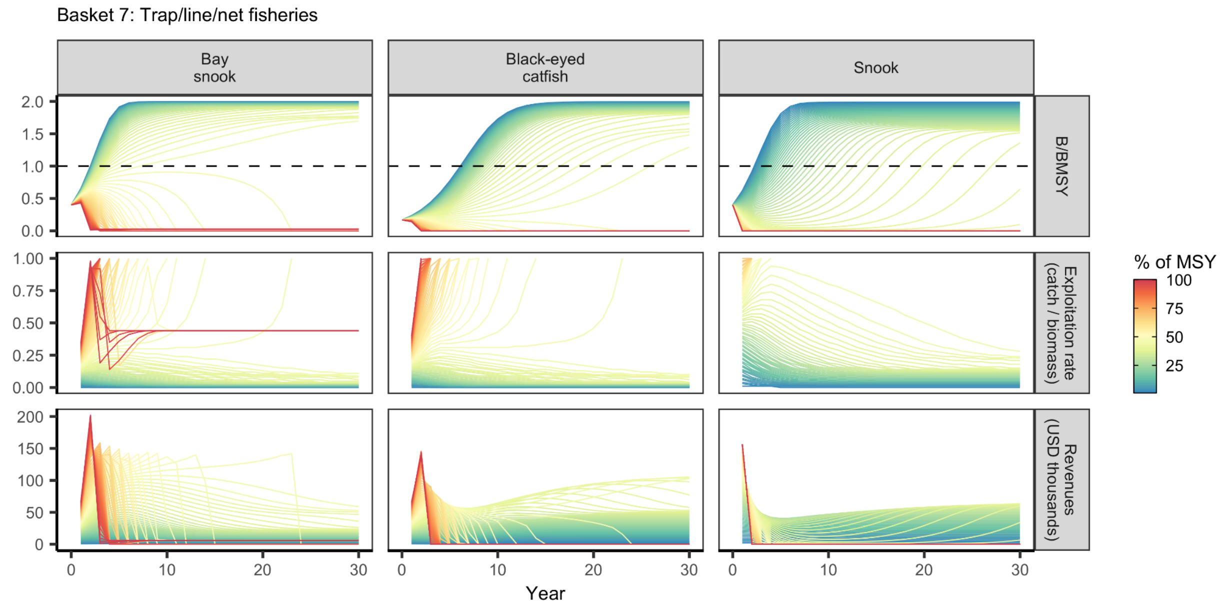

Figure S11. Population trajectories for species managed in Basket 7 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

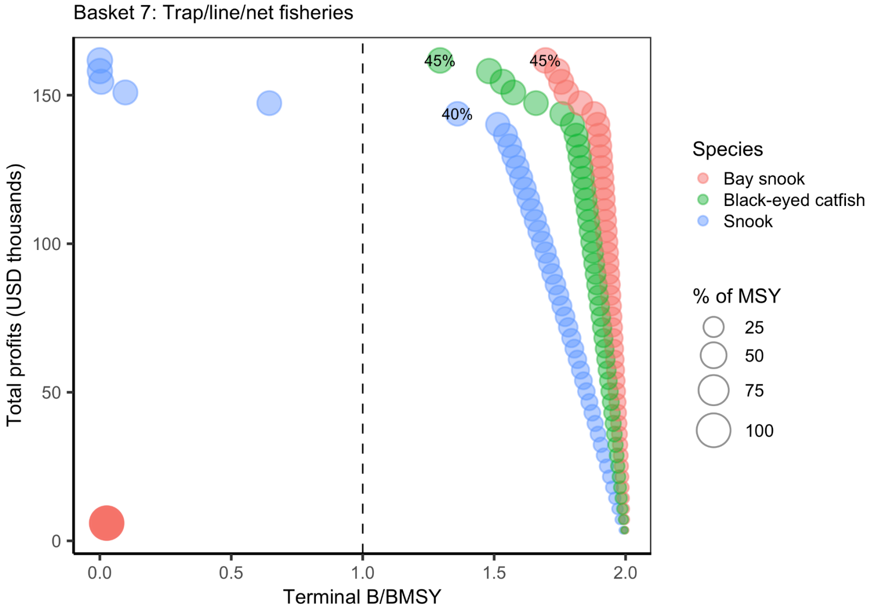

Figure S12. Tradeoffs between stock status and profits for species managed in Basket 7 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 8

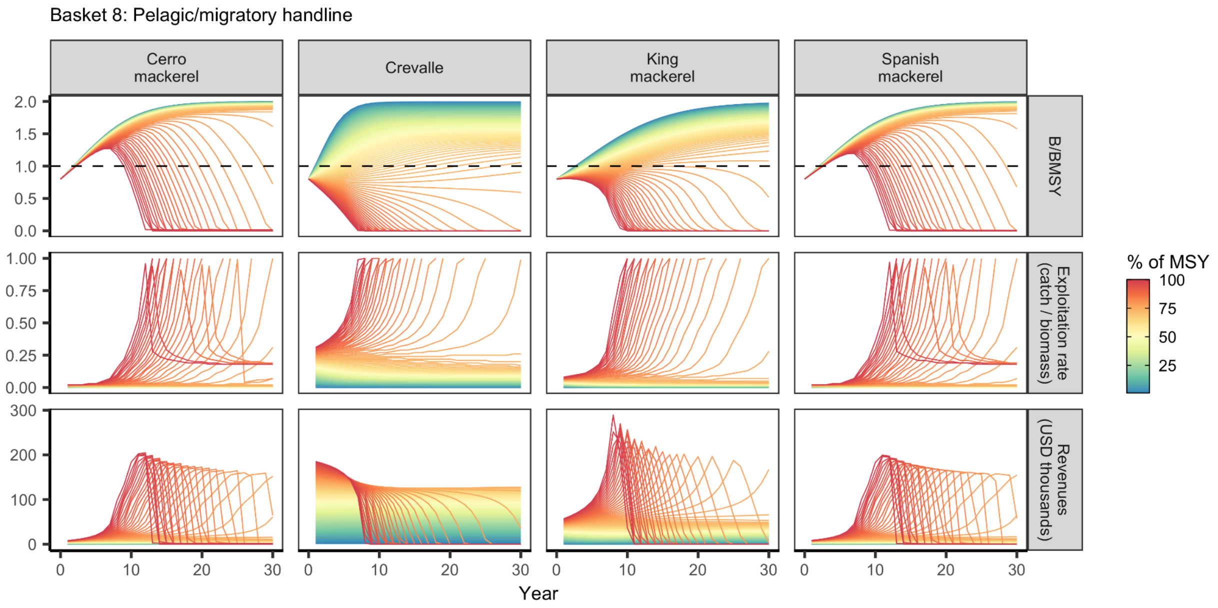

Figure S13. Population trajectories for species managed in Basket 8 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

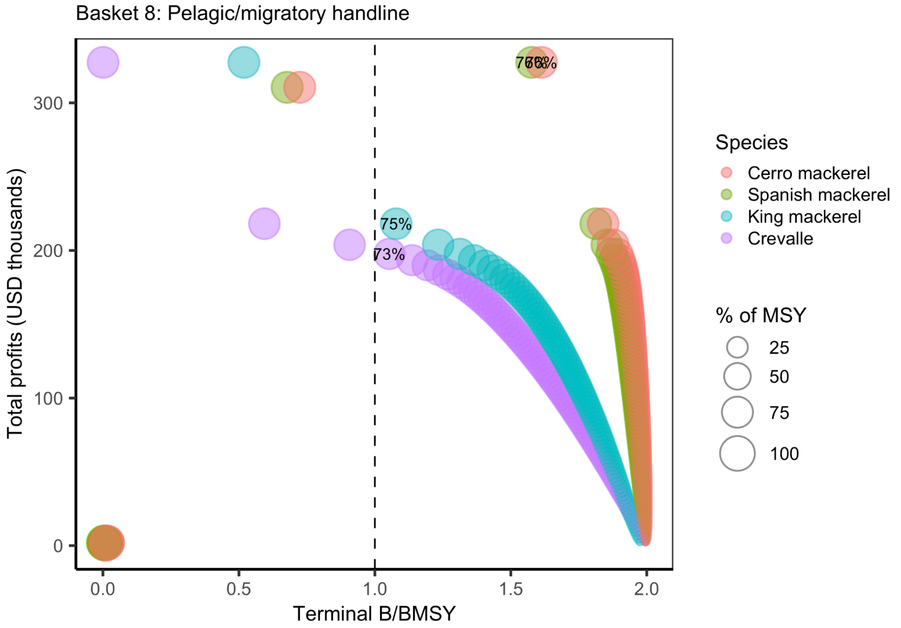

Figure S14. Tradeoffs between stock status and profits for species managed in Basket 8 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 9

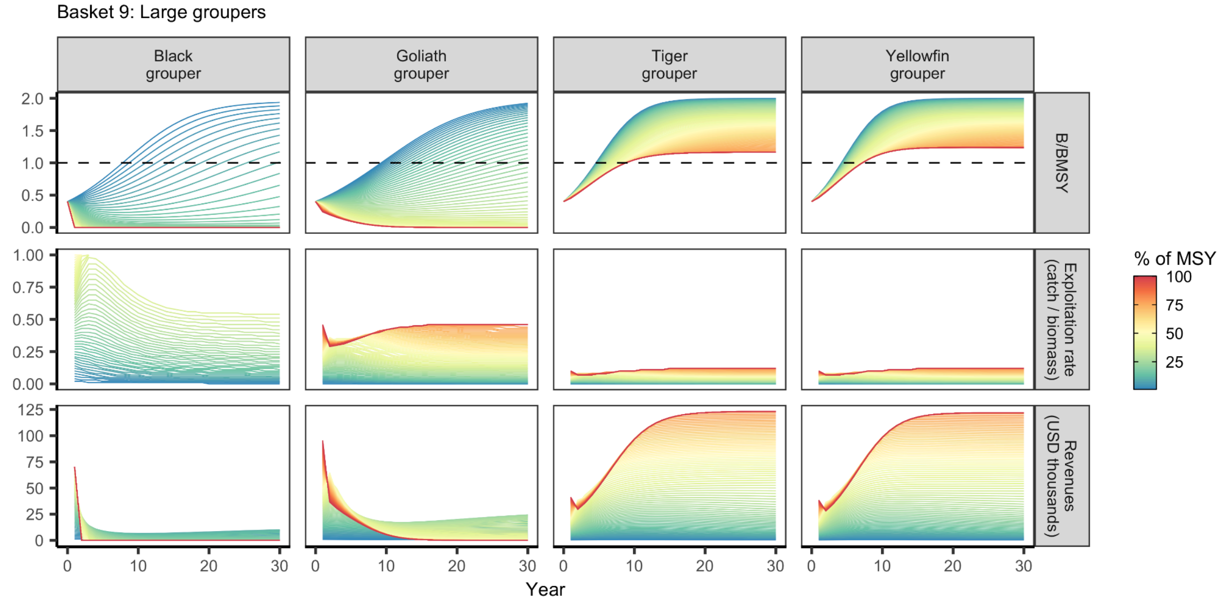

Figure S15. Population trajectories for species managed in Basket 9 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

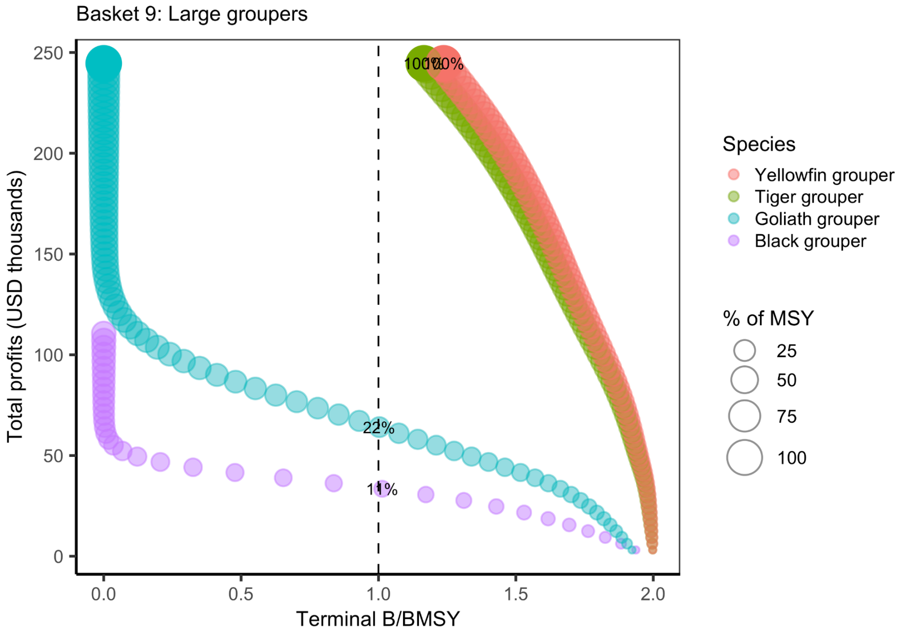

Figure S16. Tradeoffs between stock status and profits for species managed in Basket 9 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 10

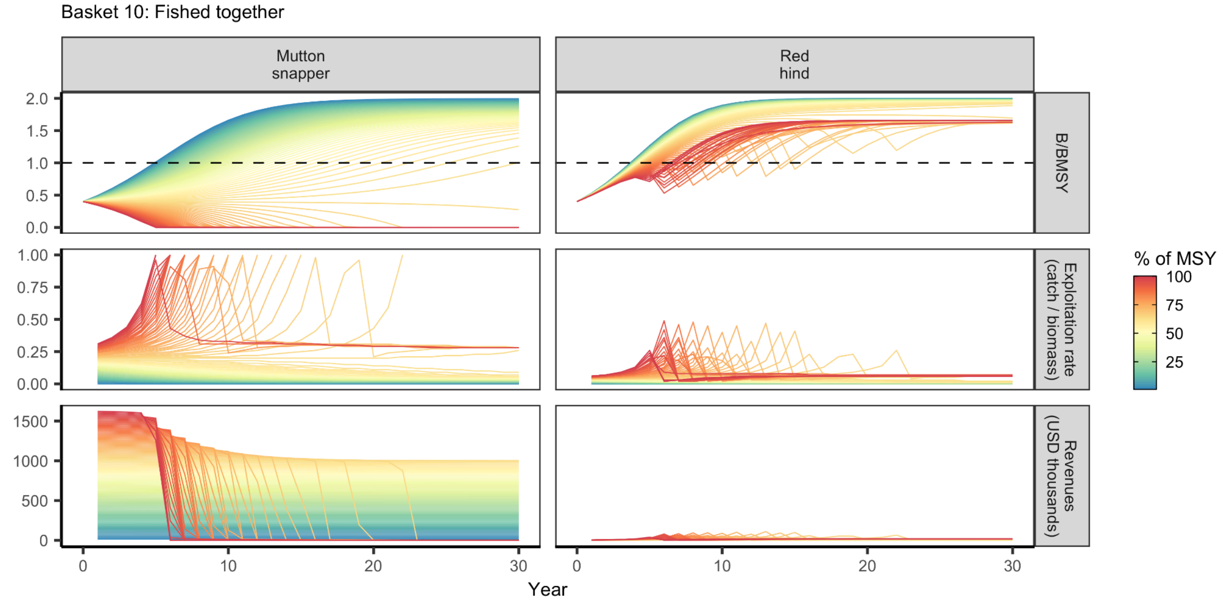

Figure S17. Population trajectories for species managed in Basket 10 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

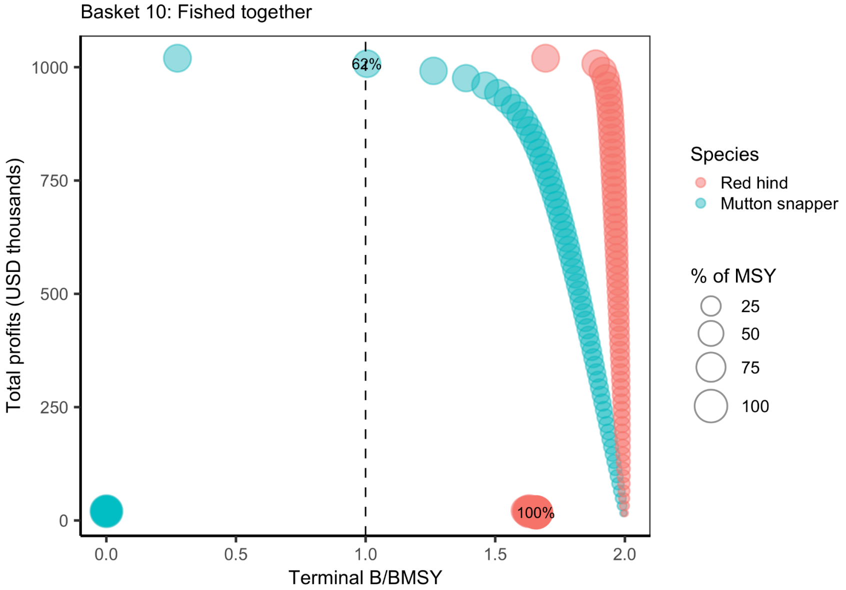

Figure S18. Tradeoffs between stock status and profits for species managed in Basket 10 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Basket 13

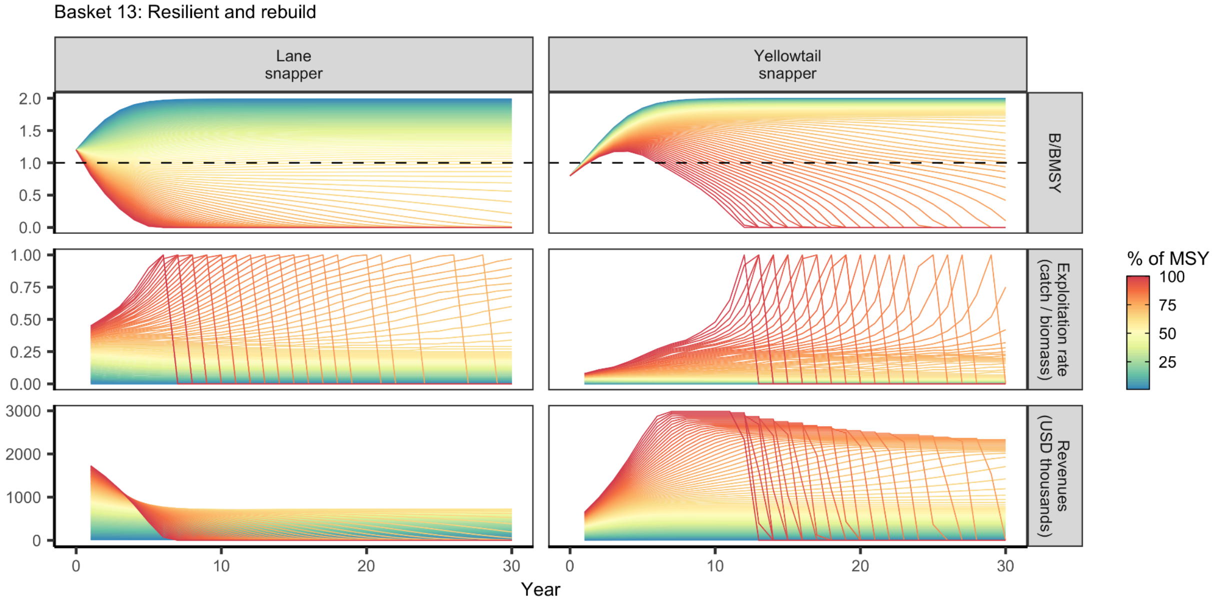

Figure S19. Population trajectories for species managed in Basket 13 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket.

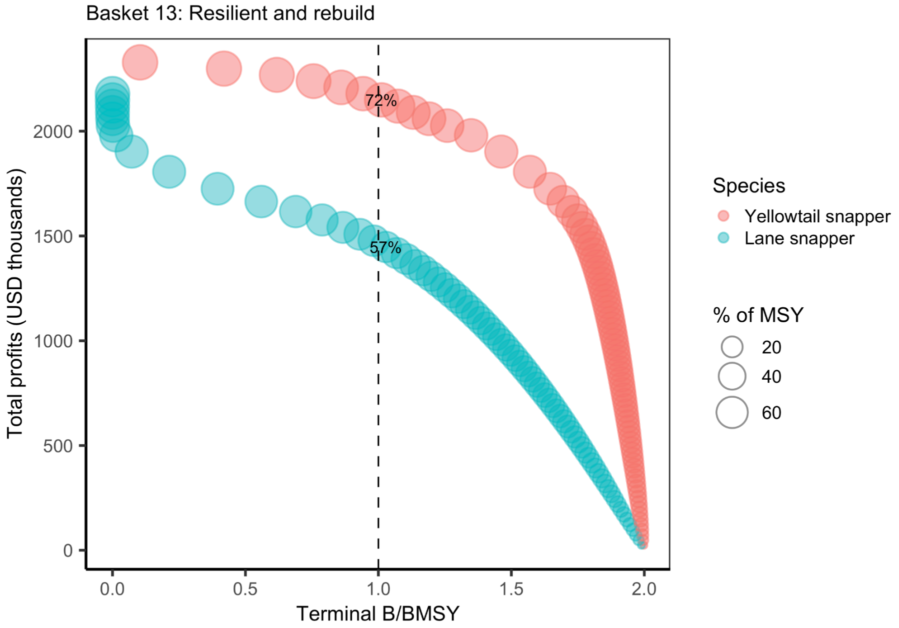

Figure S20. Tradeoffs between stock status and profits for species managed in Basket 13 under different harvest policies. Harvest policies set the basket-wide quota as a percentage of the summed maximum sustainable yield for each of the species in the basket. The largest percentage that would allow each species to remain above the BMSY management target is labeled. The species with the smallest value represents the most limiting species.

Appendix B. Detailed methods

We propose a modified Gordon-Schaefer model to identify fishermen’s criteria for allocating effort within and across clusters and how managers can set harvest limits. The modifications are (i) incorporating a catchability matrix and (ii) distributing the quota limits through a basket arrangement matrix.

Quota basket bioeconomic model

We assume the species’ life histories are independent; thus, we are not contemplating any prey-predator interactions. For fishermen, we take a myopic approach with the following payoff function:

$$\pi = \max_{E} P^t BQE - \frac{1}{2} E^t CE$$

$$\text{where:} H = BQE \geq 0 \qquad (1)$$

$$\text{s.t.} Z \geq MBQE \geq 0$$

$$b_{ss}, q_{sn}, e_{n1} \geq 0$$

Where:

- s: number of species
- n: number of technologies
- j: number of baskets
- P: nx1 price per s vector
- B: sxs diagonal matrix for s stocks
- Q: sxn matrix for catchabilities
- C: nxn array of costs per n
- E: nx1 vector of efforts per n
- M: jxs matrix for basket arrangement
- Z: jx1 vector of harvest limits

B and C are diagonal matrices that store the stocks ($B = b_{ss}$), and private costs ($C = c_{nn}$), respectively. We are not considering switching costs or delays from shifting technologies between periods. However, they can be easily incorporated through a transition matrix or by using the off-diagonal costs and modifying our effort vector. On the revenue side, our prices are constant. In other words, we need to model the demand of each species.

A multi-species fishery also raises the question of whether discarding and high-grading are possible. We assumed that both aren’t possible, and the harvest of every species within a basket is sold at full price. In the case of multiple coexisting baskets, the species that don’t share a prioritized basket belong to an ”others” basket.

The equation of motion for the stock of each species s:

$$b_{t+1} = b_t - r_s * ((exp(T_t - \frac{1}{n} * \sum_{t=1}^{t} T_{t-1}) * \theta_s) * b_t * (1 - b_t/k_t) - h_s \qquad (2)$$

Where:

- s: species s
- t: period t
- T: sea surface temperature
- θ: climate parameter of stock s
- b: biomass of stock s
- k: carrying capacity of stock s
- h: harvest of stock s

Equation 2 helps remind us that biological parameters are relevant when determining the marginal revenue of each species and basket. In this context, we assume the biological parameters (r_s, m, k_s) don’t change the catchabilities (q_{sn}). However, the SST anomalies can affect the intrinsic growth through the parameter θ, which can be a positive or negative number. For the current document, we are not evaluating the effect of SST, and, in consequence, θ is zero.

Assumptions

- Independent life histories: no prey-predator relationships
- Myopic optimization (discount rate equal to 1)
- No uncertainty, external shocks, or information asymmetry
- Bycatch species sold for full price
- No harvested species are discarded back into the ocean
- One generic technology and the same costs for all technologies
- No switching costs or technology implementation delays
- Demand and price are exogenous
- Quotas don't affect biological parameters
- Biological parameters don't affect catchability over time
- No size, age, or spatial considerations

Appendix C. Data treatment

Life cycle parameters

We used the FishLife R package (Thorson et al., 2023) to obtain intrinsic growth (r) estimates for the 48 species in Belize (See Appendix 1). Moreover, FishLife provided data about annual harvest (metric tons) and harvest value ($) for 24 species.

With intrinsic growth, annual catch, and catch per fishing gear type, it is possible to estimate the carrying capacities, MSY, and catchability coefficients for 24 species.

Carrying capacity (K)

We used the CMSY method (Froese et al. 2017) to estimate K through the datalimited2 R Package (Free, 2022). The datalimited2 CMSY command requirement of prior lower and upper bounds for r is satisfied by subtracting and adding the proposed values below around the FishLife r estimates.

Table S1. Carrying capacity (K), intrinsic growth (r), and bounds.

Scientific name	CMSY K	Fishlife r	Datalimited 2 r	Lower bound	Upper bound	Bound
Acanthocybium solandri	81.63	0.51	0.51	0.5	0.52	0.01
Caranx hippos	2197.85	1.05	0.47	0.25	1.85	0.8
Centropomus undecimalis	205.94	0.71	0.71	0.7	0.72	0.01
Coryphaena hippurus	17.28	0.86	0.87	0.85	0.87	0.01
Epinephelus guttatus	163.64	0.4	0.4	0.39	0.41	0.01
Epinephelus itajara	522.71	0.15	0.16	0.14	0.16	0.01
Epinephelus striatus	1116.6	0.32	0.32	0.31	0.33	0.01
Gerres cinereus	297.12	1.17	1.18	1.16	1.18	0.01
Haemulon plumierii	373.49	0.66	0.66	0.65	0.67	0.01
Haemulon sciurus	971.36	0.73	0.49	0.33	1.13	0.4
Lachnolaimus maximus	209.74	0.68	0.68	0.67	0.69	0.01
Lutjanus analis	8156.87	0.3	0.3	0.29	0.31	0.01
Lutjanus apodus	321.91	0.44	0.44	0.43	0.45	0.01
Lutjanus griseus	786.59	0.21	0.22	0.2	0.22	0.01
Lutjanus jocu	755.31	0.24	0.24	0.23	0.25	0.01
Lutjanus purpureus	1522.24	0.25	0.29	0.15	0.35	0.1
Lutjanus synagris	2547.86	0.55	0.55	0.54	0.56	0.01
Lutjanus vivanus	877.02	0.22	0.23	0.21	0.23	0.01
Mycteroperca bonaci	125.81	0.2	0.2	0.19	0.21	0.01
Ocyurus chrysurus	5457.93	0.52	0.52	0.51	0.53	0.01
Rachycentron canadum	238.34	0.45	0.46	0.44	0.46	0.01

Scomberomorus cavalla	1155.37	0.16	0.16	0.11	0.56	Special
Seriola dumerili	272.7	0.43	0.44	0.42	0.44	0.01
Sphyraena barracuda	3162.35	0.17	0.17	0.16	0.18	0.01

However, we kept the datalimited2 r values because consistency between K is a priority.

It is possible to find the carrying capacity for the other 28 species (without harvest time series data) by regressing K concerning r. For the 24 selected species with available data, we obtained the following relationship with an R2 of 0.17:

$$\ln(K) = 7.4 - 2.38 * r \qquad (3)$$

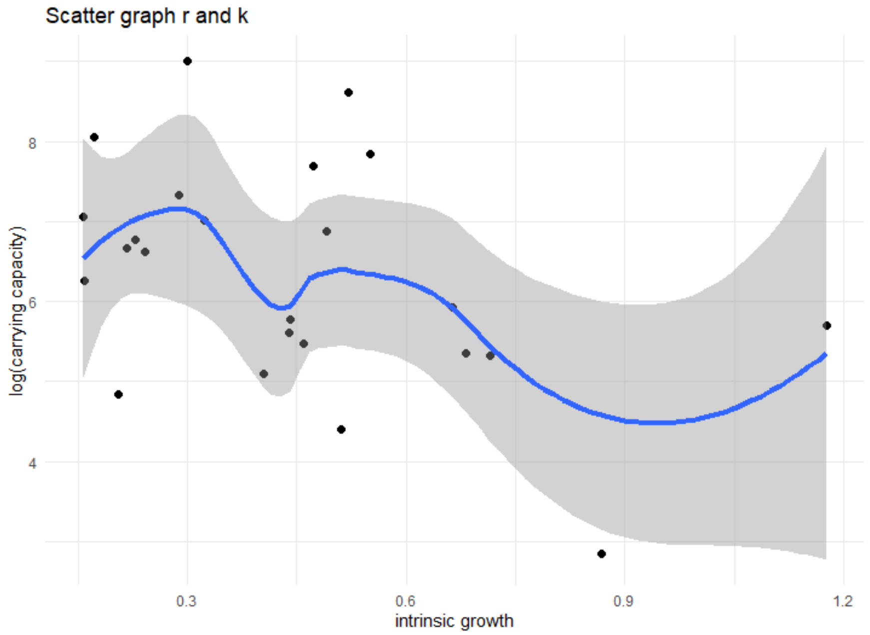

Figure S21. Scatter plot of intrinsic growth and log(carrying capacity) among Belize's species with available data (24 species). The regression line is rendered in blue, and confidence intervals are denoted in gray.

Maximum Sustainable Yield (MSY)

We obtained MSY from datalimited2. For the species without catch data, we applied the following formula:

$$MSY = 0.25 * K * r$$

Prices (p) and costs (c)

The division between average annual value and average annual catch is our selected proxy for price per species.

For the species without historical harvest data, we assume their price is equal to the average price of the species in the same basket.

All effort per technology has a symbolic cost of 1 USD. Thus, prices are the primary source of profits.

Effort (E)

We took the number of vessels reported in Belize's profile for FAO (2021):

Table S2. Total vessels in Belize.

Year	1980	1990	2000	2010	2015	2016	2017
Boats	800	800	1070	700	510	560	560

For our simulations, we assumed the available effort in 2019 is similar to 2017.

Catchability (q)

We obtain the relationship between the catchability in the year 2019 (our last available observation) that share the same basket through the following formula:

$$\frac{q_i}{q_j} = \frac{h_i k_j u_j}{h_j k_i u_i} \qquad (4)$$

Where:

- h: harvest in 2019 for species i or j
- k: carrying capacity of species i or j
- u: depletion rate

We build proportions around the species with the highest catch in 2019 (q1). Once we have the relationship, we obtain the CPUE for the species with the highest catch (q1) by dividing its assumed harvest in 2019 by the number of vessels (560). Then, we use the above proportion to get the species' catchability.

Biomass at period 0

We derived from UNCTAD (2022), where healthy, moderate, and unhealthy statuses are assumed to correspond to 60% (1.2 B/B_{MSY}), 40% (0.8 B/B_{MSY}), and 20% (0.4 B/B_{MSY}) of unfished biomass, respectively.

Appendix D: Mathematical analysis

In this section, we expand our analysis to a more compressive setting and evaluate whether the lessons of our analysis persist for s species and n technologies. We generalize a simple setting and make some propositions about the fishermen’s effort allocation.

Static analysis: fishermen case without a harvest limit

We use equation 1 without harvest limits:

$$\pi = P'BQE - \frac{1}{2}E'CE \quad (5)$$

We take the FOC on E:

$$\pi = P'BQ - E'C = 0$$
$$= P'BQ = E'C$$
$$= P'BQC^{-1} = E' \quad (6)$$

This is the optimal effort allocation.

Without cap: s=2, n=2

This section explores the detailed solution for 2 species and 2 technologies. In this context, we define the following matrices:

$$P' = \begin{bmatrix} p_{11} & p_{21} \end{bmatrix}$$

$$B = \begin{bmatrix} b_{11} & 0 \\ 0 & b_{22} \end{bmatrix}$$

$$Q = \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{bmatrix}$$

$$E' = \begin{bmatrix} e_{11} & e_{21} \end{bmatrix}$$

$$C = \begin{bmatrix} c_{11} & 0 \\ 0 & c_{22} \end{bmatrix}$$

$$C^{-1} = \begin{bmatrix} 1/c_{11} & 0 \\ 0 & 1/c_{22} \end{bmatrix}$$

Considering these matrices, our optimal efforts are:

$$\begin{bmatrix} (p_{11} * b_{11} * q_{11} + p_{21} * b_{22} * q_{21})/c_{11} \\ (p_{11} * b_{11} * q_{12} + p_{21} * b_{22} * q_{22})/c_{21} \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \end{bmatrix}$$

We observe each effort is marginal revenue per unit of effort over the marginal costs. The costs cannot be zero. Their effort allocation decision depends on which technology harvests more, which stock is bigger, which stock price is higher, and which technology cost is smaller. However, remember that each biomass depends on its intrinsic growth (r), health status (b/K), and previous harvest decision (which we didn't consider in a myopic optimization). Then our above expression becomes:

$$\begin{bmatrix} (p_{11} * b_{11}(r_1, b_{11}/K_1) * q_{11} + p_{21} * b_{22}(r_2, b_{22}/K_2) * q_{21})/c_{11} \\ (p_{11} * b_{11}(r_1, b_{11}/K_1) * q_{12} + p_{21} * b_{22}(r_2, b_{22}/K_2) * q_{22})/c_{21} \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \end{bmatrix}$$

Notice that stock parameters influence effort allocations if their relevant catchabilities are positive. If stocks, prices, and costs equal 1, the effort comparison is according to their catchabilities.

If $q_{12} = q_{21} = 0$, we obtain the single species results (without bycatch):

$$\begin{bmatrix} (p_{11} * b_{11} * q_{11})/c_{11} \\ (p_{21} * b_{22} * q_{22})/c_{21} \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \end{bmatrix} \quad (7)$$

Without cap: s=3, n=2

This section explores the detailed solution for 3 species and 2 technologies. We define the following matrices:

$$P' = \begin{bmatrix} p_{11} & p_{21} & p_{31} \end{bmatrix}$$

$$B = \begin{bmatrix} b_{11} & 0 & 0 \\ 0 & b_{22} & 0 \\ 0 & 0 & b_{33} \end{bmatrix}$$

$$Q = \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \\ q_{31} & q_{32} \end{bmatrix}$$

$$E' = \begin{bmatrix} e_{11} & e_{21} \end{bmatrix}$$

$$C = \begin{bmatrix} c_{11} & 0 \\ 0 & c_{22} \end{bmatrix}$$

$$C^{-1} = \begin{bmatrix} 1/c_{11} & 0 \\ 0 & 1/c_{22} \end{bmatrix}$$

Considering these matrices, our optimal efforts are:

$$\begin{bmatrix} (p_{11} * b_{11} * q_{11} + p_{21} * b_{22} * q_{21} + p_{31} * b_{33} * q_{31})/c_{11} \\ (p_{11} * b_{11} * q_{12} + p_{21} * b_{22} * q_{22} + p_{31} * b_{33} * q_{32})/c_{21} \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \end{bmatrix}$$

We notice that adding one additional species means increasing the marginal revenue of each technology (in the case that all catchabilities are positive).

Without cap: generalization

It is possible to generalize for s species and n technologies in the following way:

$$\begin{bmatrix} (p_{11} * b_{11} * q_{11} + p_{21} * b_{22} * q_{21} + ... + p_{s1} * b_{ss} * q_{s1})/c_{11} \\ (p_{11} * b_{11} * q_{12} + p_{21} * b_{22} * q_{22} + ... + p_{s1} * b_{ss} * q_{s2})/c_{21} \\ ... \\ (p_{11} * b_{11} * q_{1n} + p_{21} * b_{22} * q_{2n} + ... + p_{s1} * b_{ss} * q_{sn})/c_{n1} \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \\ ... \\ e_{s1} \end{bmatrix} \quad (8)$$

Propositions

Proposition 1. If all marginal prices and private costs across species are the same, species within the basket with similar traits (r, k, b/k, q/r) will perform better for conservation goals.

Remember our equation of motion for stock:
$b_{t+1} = b_t - r_s * b_t * (1 - b_t/k_t) - h_s$

We obtain $r_s * b_t * (1 - b_t/k_t) = h_s$ in steady state for each species individually. To avoid overexploitation, the harvest across species should be the same ($h_1 = h_2 = \ldots = h_s$)). If we take the relationship between 2 stocks:

$$\frac{r1\left(1-\frac{B1}{K1}\right)}{q1} = \frac{r2\left(1-\frac{B2}{K2}\right)}{q2}$$

Harvest rates can be similar if species have similar parameters or a combination of parameters that obtain the rate. The above expression can be reinterpreted as the vulnerability rate multiplied by the initial depletion status.

Proposition 2. If all species traits are the same, the fishermen allocate effort to the technology with the greatest sum of catchabilities.

Let's start with the generalized result without a cap for one period:

$$\begin{bmatrix} (p_{11} * b_{11} * q_{11} + p_{21} * b_{22} * q_{21} + \ldots + p_{s1} * b_{ss} * q_{s1})/c_{11} \\ (p_{11} * b_{11} * q_{12} + p_{21} * b_{22} * q_{22} + \ldots + p_{s1} * b_{ss} * q_{s2})/c_{21} \\ \ldots \\ (p_{11} * b_{11} * q_{1n} + p_{21} * b_{22} * q_{2n} + \ldots + p_{s1} * b_{ss} * q_{sn})/c_{n1} \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \\ \ldots \\ e_{s1} \end{bmatrix}$$

If all biological (r, k, b0) traits and economic traits (p, c) are the same, we have:

- $p_{11} = p_{21} = \ldots = p_{s1} = p,$
- $c_{11} = c_{21} = \ldots = c_{n1} = c$
- $b_{11} = b_{22} = \ldots = b_{ss} = b.$

Then:

$$\begin{bmatrix} (p * b * q_{11} + p * b * q_{21} + \ldots + p * b * q_{s1})/c \\ (p * b * q_{12} + p * b * q_{22} + \ldots + p * b * q_{s2})/c \\ \ldots \\ (p * b * q_{1n} + p * b * q_{2n} + \ldots + p * b * q_{sn})/c \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \\ \ldots \\ e_{s1} \end{bmatrix}$$

$$\begin{bmatrix} (p * b * (q_{11} + q_{21} + ... + q_{s1})/c \\ (p * b * (q_{12} + q_{22} + ... + q_{s2})/c \\ ... \\ (p * b * (q_{1n} + q_{2n} + ... + q_{sn})/c \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \\ ... \\ e_{s1} \end{bmatrix}$$

We observe the fishermen will allocate effort to the technology that has the biggest summation of catchabilities.

Proposition 3. If the best targeting technologies are perfect for each species, any quota basket configuration t will have the same results as an individual management scheme.

For the general case, there is no bycatch if all non-diagonal q is zero ($q_{sn} = 0$ where $s \neq n$). Then, we obtain the following:

Which is the result of individual quota management.

$$\begin{bmatrix} (p_{11} * b_{11} * q_{11})/c_{11} \\ (p_{21} * b_{22})/c_{21} \\ ... \\ (p_{s1} * b_{ss} * q_{sn})/c_{n1} \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \\ ... \\ e_{s1} \end{bmatrix}$$

Proposition 4. Considering the same biological and economic traits, a species whose best target technology has perfect targeting must not be part of a quota basket.

Let's return to the conclusion of Proposition 2:

$$\begin{bmatrix} (p * b * (q_{11} + q_{21} + ... + q_{s1})/c \\ (p * b * (q_{12} + q_{22} + ... + q_{s2})/c \\ ... \\ (p * b * (q_{1n} + q_{2n} + ... + q_{sn})/c \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \\ ... \\ e_{s1} \end{bmatrix}$$

Assume all the catchabilities are the same (q) except q_{1n}:

$$\begin{bmatrix} (p * b * (q_{11} + q_{21} + ... + q_{s1})/c \\ (p * b * (q_{12} + q_{22} + ... + q_{s2})/c \\ ... \\ (p * b * (q_{1n} + q_{2n} + ... + q_{sn})/c \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \\ ... \\ e_{s1} \end{bmatrix}$$

From proposition 2, the allocation on e_{s1} will be greater if $q_{1n} > q$. Then, let's pretend technology n has perfect targeting ($q_{2n} = ... = q_{sn} = 0$):

$$\begin{bmatrix} (p * b_{11} * q + p * b * (n-1) * q)/c \\ (p * b_{11} * q + p * b * (n-1) * q)/c \\ \cdots \\ (p * b_{11} * (q_{1n})/c \end{bmatrix} = \begin{bmatrix} e_{11} \\ e_{21} \\ \cdots \\ e_{s1} \end{bmatrix}$$

If $q_{1n} > q$, the fishermen will choose effort es1, and this decision won't affect the rest of the species within a basket. However, if $q_{1n} < q$, the fishermen will choose a different technology that can affect the rest of the species within a basket.

Proposition 5. Increasing the number of baskets will have diminishing returns as it approaches an individual management scheme (basket of 1 element). However, the risk of a failed design will be reduced.

Simulating different scenarios shows that it is possible to obtain better and worse outcomes than open access (all species in one basket). As we have seen, there are many chances of making the wrong configurations. However, if we use more baskets, we will likely avoid this mistake.

Assume we have five species and use one basket for each one (individual management), and let's work with backward induction:

- If we reduce the number of baskets to 4, putting three species in individual management schemes is possible, and the remaining two have to share a basket. If we individually manage the most profitable ones, the success of the basket will depend on the previous propositions.
- If we reduce the number of baskets to 3, putting two species in individual management schemes is possible, and the remaining three must share a basket. If we individually manage the most profitable ones, the success of the basket will depend on the previous propositions. We are farther from the individual management. However, we can also create two baskets of 2 and one basket of 1, but their performance will depend on the similarities across species (to achieve similar effort).
- If we reduce the number of baskets to 2, we can repeat the same logic but face more basket arrangements. However, it is more likely to worsen because we are far away from individual management.
- If we reduce the number of baskets to 1, we depend on the species targeting. We don't have a choice.

Moving from one basket (all species) to a two-basket scheme can greatly improve fishery performance. However, more baskets will mean that we are closer to individual management, and thus, there will be fewer basket arrangements to choose from. Collado et al. (2021) showed this numerically.