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Quota Baskets: Exploring alternative groupings for fisheries management

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management for the Bren School of Environmental Science & Management

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Abstract

Good fisheries management is resource intensive, and as a result, many fisheries fail to achieve desirable fisheries outcomes. Quota basket management may have the potential to improve fisheries management with a relatively small number of quotas, resulting in reduced fisheries costs, improved ecological and economic outcomes, and more sustainable fisheries. Quota basket management divides a fishery into groups where fish share a common trait and sets a harvest quota for each group. We explore the feasibility of quota basket management in two ways: by using a modified surplus production model to explore different quota basket management schemes, and through a review of similar management schemes used in real fisheries. Our results show that quota baskets have the potential to improve some fisheries management schemes, but that quota basket success is highly dependent on how quota baskets are constructed and how they influence the target fishery. Our modeling results show that carefully designed quotas increase profits for an example fishery, but also show that poorly designed quota baskets reduce profits and stock levels compared to a global quota. These results are echoed in our case studies, where quota baskets drastically improved a fishery outcome. Overall, when carefully designed, quota baskets can improve fisheries outcomes with a simple management scheme, but without careful design consideration, carry considerable risk to fisheries.

Executive Summary

Quota basket management is a fisheries management strategy where fish in a fishery are grouped by a common trait and then managed in that group. When fish are grouped and managed in well-thought-out ways, we hypothesize quota baskets can improve fishery outcomes with lower monitoring and enforcement costs. Quota baskets are applicable in many of the world's fisheries. Many fisheries fail to achieve management targets because high management costs prevent adequate monitoring, enforcement, data, stakeholder engagement, or strong institutions (Pomeroy, 2012; Costello, et al., 2012; Sumaila et al., 2012; Ye et al., 2013; Costello et al., 2016; FAO, 2020). The quota basket concept–better outcomes with fewer management units–is targeted at fisheries that want to improve management but cannot implement complicated and expensive schemes.

Well-designed quota baskets might improve fisheries management, but poorly designed quota baskets may negatively affect fishery outcomes. This poor design has led some authors to conclude that quota baskets are too risky to consider for real world management (Bonzon et al., 2013). However, there are no formal studies exploring quota baskets as a fisheries management strategy.

This report analyzes how quota basket management can be applied to fisheries, when it can succeed, and when it can fail. First, we use a modified surplus production model to determine how different quota basket groupings affect fishery outcomes in a profit-maximizing fishery. We then corroborate our theoretical results with two case studies comparing a quota basket scheme to more traditional management in groundfish fisheries in the Pacific Ocean. Finally, we use our model and case studies to develop guidelines for implementing quota baskets that achieve better fishery outcomes.

Our results show that quota basket management can improve on simple management schemes in terms of profit maximization. Additionally, we find that well-designed baskets can lead to improved fishery profits and stock health, while poorly designed baskets risk overexploited species and hinder economic outcomes. Furthermore, we show that quota baskets can alter fishers targeting dynamics and that this mechanism leads to highly varied fisheries outcomes that depend on the basket construction, the characteristics of fish involved, and the harvest limits. We corroborate these results with two case studies, where we find that a single quota basket in the Bering Sea allowed fishing of valuable stocks while protecting weak stocks. As a contrast, we find that poorly set single species harvest limits in the Pacific groundfish fishery allowed fishers to fish weak stocks well below sustainable levels.

Our analysis shows that quota baskets can be a highly successful fisheries management strategy, and can improve profit outcomes with a simple quota. However, we also show that poorly constructed quota baskets can lead to reduced profits and poor biomass outcomes compared to even simpler management schemes. A quota basket's success involves understanding the target fishery and how a quota basket shifts fishing and fisheries dynamics in pursuit of a management goal. As a result, the success of a quota basket depends highly on its design, and we conclude with a simple framework of guiding principles for well designed quota baskets. For quota baskets to succeed in a real world management scenario, significant fishery specific work is

necessary to pick a basket grouping that achieves a fishery's goals. However, we believe that well thought out quota baskets can improve some fisheries through relatively simple management schemes.

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Objectives and Significance

Main objective

Our main objective is to develop quota basket theory. This report will help managers and decision-makers determine whether quota baskets are an appropriate management strategy for a fishery.

Other objectives

1. Explore the concept of quota baskets for fisheries management. Outline the benefits, drawbacks, and potential effects of quota basket management.
2. Develop a model that demonstrates how different fishery groupings affect fishery profits and stocks.
3. Analyze examples of quota basket management in the real world.

Our client, the Environmental Defense Fund (EDF) will use this research as a first step in determining whether quota baskets are a viable fisheries management strategy.

Significance

Fisheries management strategies often try to maximize revenue and food production while sustaining fish populations. However, global fisheries management often does not meet these goals and is prone to collapse (Worm et al., 2006). Well-managed fisheries result from a lengthy ecosystem and economic studies and often require multifaceted management initiatives that are difficult to enforce (Chesapeake Bay Ecosystem Advisory Panel, 2006). Most countries do not have the resources to implement the best practices in management, and the resulting strategies do not balance stock health, food provision, or profit generation (Worm et al., 2009; Costello et al., 2012). Costello, Gaines, and Lynham (2008) suggest that institutional reforms and adequate management can prevent and rebuild overfished stocks.

In this project, we expand the concept of quota baskets as a fisheries management strategy. We see quota baskets as a less resource-intensive strategy that can capture some of the economic and ecological benefits of complex fisheries models. We hypothesize that a well-implemented quota basket management scheme can incentivize sustainable fishing and promote high economic yields while remaining relatively easy to implement and enforce. A well-designed basket may reflect ecosystem and/or economic nuance at a finer scale than other simple management schemes.

The EDF's Oceans team, which focuses on fisheries reform, strives to promote science-based, real-world-tested fisheries management approaches. Their approach prioritizes economically, socially, and environmentally sustainable interventions. As members of EDF's China team, our clients are particularly interested in the potential application of quota baskets in China. Currently, China's fisheries management prioritizes ease of implementation and implements a summer moratorium to rebuild fish stocks. Quota basket management presents a management strategy that might improve fishery outcomes while keeping implementation costs low, including in China. While conceptually attractive, evidence that quota basket management is worth pursuing is lacking. This project will provide EDF insight into the efficacy and feasibility of quota baskets.

Background

The problem with current fisheries management

Global fisheries management strategies range from simple (unregulated open-access fishery) to incredibly complex (ecosystem-based management) schemes. Simple schemes often lead to stock collapse and poor economic outcomes (Grébovalc & Munro, 1999; Costello et al., 2010; Kraan, 2011), while well-managed fisheries maximize economic results, improve planning, and rebuild stocks through extensive monitoring and enforcement (Hillborn, et al., 2020). While fisheries management aims to avoid collapsed stocks and improve economic yields, implementing successful management is resource-intensive and hard to achieve for fisheries without scientific data and capable institutions (Costello et al. 2008; 2016; Hillborn, et al., 2020). As a result, while most fisheries try to improve outcomes through management, many fisheries do not have the resources to achieve their goals. These fisheries opt for “middle ground” management, where some management exists, but with inadequate monitoring, enforcement, data, stakeholder engagement, or weak institutions (Pomeroy, 2012; Costello, et al., 2012; Sumaila et al., 2012; Ye et al., 2013; Costello et al., 2016; FAO, 2020). One consequence of “middle ground” management is that these strategies often fail to achieve sustainable fisheries, with one study estimating that 64% of the world’s stocks still need rebuilding (Worm et al., 2009). Quota baskets, the focus of this report, might help improve these “middle ground” fisheries management strategies.

A major driver of fisheries management problems is that much of fisher behavior is motivated by profit maximization (Willmann, 1997; Andersern et al., 2015; Jacobsen et al., 2017; Battista, 2018; Birkenbach, 2018), while managers have conservation, food security, or other goals. Regulated fisheries use quotas to mediate this race for high-demand fish and to achieve other goals. Quotas force fishers to target other species or stop fishing once a quota is met. However, setting, monitoring, and enforcing quotas is resource intensive, and imperfectly set quotas lead to lost profits and unsustainable fishing. Currently, managers of “middle ground” fisheries must compromise between resource allocation and fishery outcomes (Arnason, 2000; Mangin et al., 2018). In these “middle ground” fisheries, this compromise often results in relatively simple management schemes that fail to achieve a fisheries goal.

Quota basket management is a potential solution

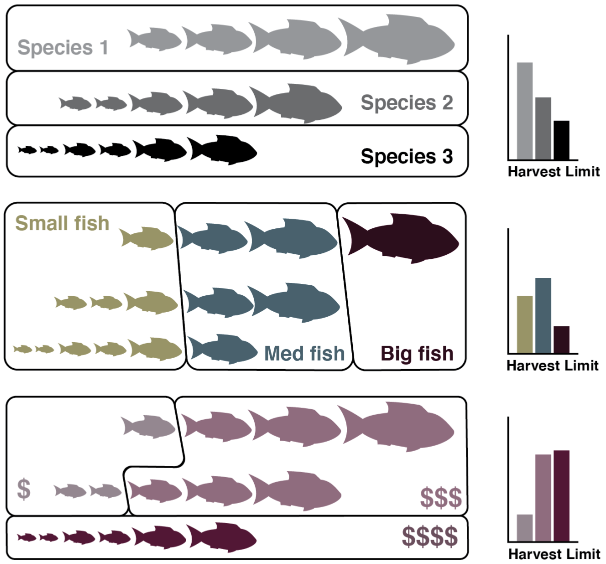


Figure 1. Examples of fisheries groupings with a quota basket scheme. *Quota basket groupings are varied. Here, three examples of quota basket groupings are shown for the same fishery. Black boxes and colors indicate groups. Harvest limit charts show example allowable catches for each basket, indicated by the color. Single species groupings set harvest limits on a species by species basis. Size groupings group fish into size baskets, independent of species, and harvest limits are set for size classes, which contain multiple species. Finally, species are grouped by their value at market, and harvest limits are set for each category.*

Quota basket management reframes fisheries management in a way that allows managers to set fewer quotas that achieve more benefit than other middle ground management schemes. In a quota basket, fisheries are grouped into management units by a common trait. These groupings are dubbed quota baskets, or baskets for short. Then, quotas are set for each group of fish. The quota basket approach encourages thinking of ways to group a fishery to achieve a management goal with fewer total quotas.

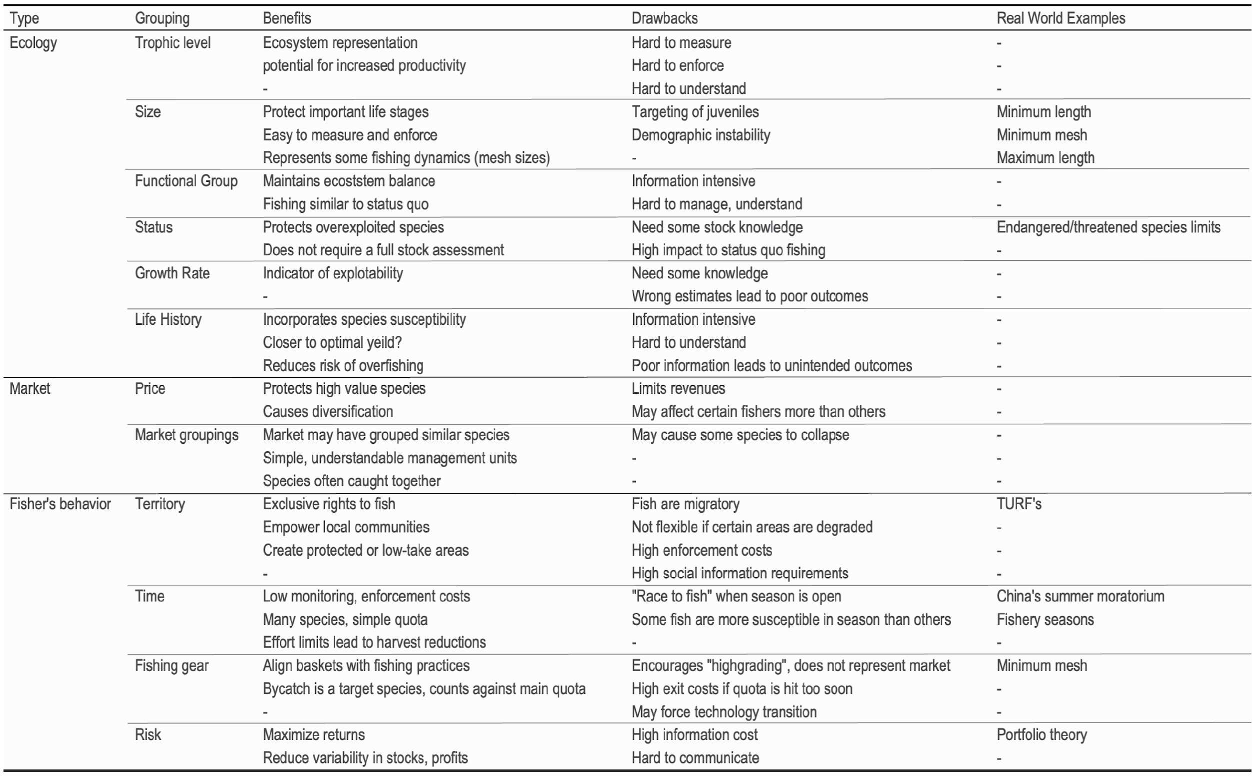
The key to designing a quota basket management scheme is picking a grouping trait for the target fishery. Quota baskets can group fish based on any number of traits, and any number of fish can exist under a basket. Grouping traits, for example, can be based on a fish's biology, like size or species; a fish's market characteristics, like price; how a fish interacts with a fishery, like being a trawling target; or social importance, like providing income for select communities.

Quota basket theory emerged from studying China's fisheries, where a very simple management scheme has manipulated fishing pressure in a way that increased the biomass output of the fisheries as a whole. China has increased the total biomass they catch from wild fisheries each year, though the rest of the world's catch has leveled off (Szuwalski et al., 2017). These trophic cascades are a result of China's limited fisheries management, which has no harvest limits for individual species and just closes fishing for part of the year. With no species quotas, fishers target high-value top predators. High targeting reduces top predators to very low numbers, and lower trophic species become much more abundant as the energy transfer loss between trophic levels is eliminated (Matsuda & Abrams, 2006). Whether the results are intentional or unintentional, China's example shows how powerful a quota basket approach may be: Szuwalski et al. found that applying a Western-style single species management plan to China's fisheries would lower total catches and revenues and threaten China's maritime food security and economic system (2017).

Chinese fisheries show that basket groupings can manipulate fishing dynamics in ways that directly affect fishery outcomes. Well designed quota baskets intentionally redirect fishing effort to achieve a fishery outcome. Baskets based on ecology, market dynamics, or fishers behavior can connect fisheries management with the underlying dynamics of a fishery. The harvest limits are set to manipulate the underlying fisheries dynamics to achieve a goal. For example, a fishery manager that wants to achieve balance within a fishery's food web but lacks resources to support a complicated scheme might set a size based quota basket. Size baskets are straightforward and related to trophic status, and a well designed size basket scheme might achieve a balanced food web without requiring an intensive ecosystem study and the resulting single species quotas (Jennings et al., 2002; Keppeller et al, 2020). Or, maybe a manager wants a management scheme that reflects how fish are sold at market, which is easy to implement and understand. Baskets might be based on market categories, like "snapper", which can be several species of fish (NOAA, 2020; HOME, 2020). Some additional groupings are found in Table 1 and Appendix 1.

Table 1. Quota basket grouping methods, their benefits, drawbacks, and real-world examples. *Table outlining different grouping characteristics for fisheries, roughly based on fisheries ecology, market dynamics, or fishers behavioral characteristics. Some benefits and drawbacks to each strategy are outlined.*

Many existing management schemes and strategies can be reinterpreted as quota baskets. We spoke to how China leverages a fishery's ecosystem structure to maximize fishery yields, and similar ecosystem responses have been observed in other fisheries around the globe (Frank et al, 2005; Myers et al., 2007; Szuwalski et al., 2017). Other examples of basket groupings include the joint strategy of Territorial Use Rights for Fisheries (TURF) and marine reserves, where a territory based basket balances food security goals for local communities with conservation (Costello & Kaffine, 2010). In Peruvian anchoveta fisheries, authorities divide the total allowable anchoveta harvest between different fishers according to fleet type, stakeholder, zone, subpopulation, season, and management goal (Kroetz et al., 2019; Kamiche & Galarza;2015; Galarza & Collado, 2013).



Type	Grouping	Benefits	Drawbacks	Real World Examples
Ecology	Trophic level	Ecosystem representation	Hard to measure	-
		potential for increased productivity	Hard to enforce	-
		-	Hard to understand	-
	Size	Protect important life stages	Targeting of juveniles	Minimum length
		Easy to measure and enforce	Demographic instability	Minimum mesh
		Represents some fishing dynamics (mesh sizes)	-	Maximum length
	Functional Group	Maintains ecoststem balance	Information intensive	-
		Fishing similar to status quo	Hard to manage, understand	-
	Status	Protects overexploited species	Need some stock knowledge	Endangered/threatened species limits
		Does not require a full stock assessment	High impact to status quo fishing	-
	Growth Rate	Indicator of explotability	Need some knowledge	-
		-	Wrong estimates lead to poor outcomes	-
	Life History	Incorporates species susceptibility	Information intensive	-
		Closer to optimal yeild?	Hard to understand	-
		Reduces risk of overfishing	Poor information leads to unintended outcomes	-
Market	Price	Protects high value species	Limits revenues	-
		Causes diversification	May affect certain fishers more than others	-
	Market groupings	Market may have grouped similar species	May cause some species to collapse	-
		Simple, understandable management units	-	-
		Species often caught together	-	-
Fisher's behavior	Territory	Exclusive rights to fish	Fish are migratory	TURF's
		Empower local communities	Not flexible if certain areas are degraded	-
		Create protected or low-take areas	High enforcement costs	-
		-	High social information requirements	-
	Time	Low monitoring, enforcement costs	"Race to fish" when season is open	China's summer moratorium
		Many species, simple quota	Some fish are more susceptible in season than others	Fishery seasons
		Effort limits lead to harvest reductions	-	-
	Fishing gear	Align baskets with fishing practices	Encourages "highgrading", does not represent market	Minimum mesh
		Bycatch is a target species, counts against main quota	High exit costs if quota is hit too soon	-
		-	May force technology transition	-
	Risk	Maximize returns	High information cost	Portfolio theory
		Reduce variability in stocks, profits	Hard to communicate	-

While well designed quota baskets can help fisheries managers achieve targets with relatively simple schemes, poorly designed quota baskets might result in management schemes that are more expensive, confusing and hard to implement, or lead to overexploitation of certain stocks. One of the only mentions of quota baskets in the literature deems them too risky because of uneven depletion within a basket (Bonzon et al., 2013). However, while the quota basket concept is not new, very little research has explored how quota baskets might be applied and the tradeoffs or dangers with different quota basket schemes (Copes, 1986; Sanchirico et al.2006; Bonzon et al., 2013).

In this project, we use a modified surplus production model to determine how different quota basket groupings affect fishery outcomes in a profit maximizing fishery. We corroborate our theoretical results with two case studies comparing a quota basket groundfish management scheme to more traditional groundfish management in the Pacific Ocean. Finally, we use our model and case studies to develop guidelines for implementing quota baskets that achieve better fishery outcomes.

Modeling Methods

3.1. Stock dynamics

Our quota-basket optimization model is based on logistic growth. The stock growth, X_{t+1} is determined by the stock's intrinsic growth rate *r*, the total stock in the water in the previous period, X_t*,* the carrying capacity, K, and the amount harvested that year, H_t..

$$X_{t+1} = X_t + rX_t \times \left(1 - \frac{X_t}{K}\right) - H_t$$

3.2. Harvest

3.2.1 Incorporating inefficient fishing

The harvest of a species is species catchability, *q* multiplied by fishing effort, *E* and stock size, *X*.

$$H = qEX$$

Since fishing is never completely efficient, we include a catchability coefficient to account for different harvest strategies within our model which describes how many fish can be caught per unit of effort. Catchability allows for situations such as the intentional (or unintentional in the case of bycatch) catch of multiple species. We refer to these harvest strategies simply as different technologies, which have predetermined catch rates, *q,* for every species in the fishery. For our modeling runs, we simulate bycatch by having technologies catch one species very well ($q = 0.04$) and all others poorly ($q = 0.01$). For simplicity reasons, we call “specialized effort” to the technology that excels in catching a specific species. Our example catchability matrix is below (Table 2), where each cell is the catchability of the species for a given technology.

Table 2: Example of catchability matrix

Technology	Species 1	Species 2	Species 3	Species 4	Species 5	Cost
1	**0.04**	0.01	0.01	0.01	0.01	1
2	0.01	**0.04**	0.01	0.01	0.01	1.5
3	0.01	0.01	**0.04**	0.01	0.01	1
4	0.01	0.01	0.01	**0.04**	0.01	2
5	0.01	0.01	0.01	0.01	**0.04**	3

Thus, the harvest of each species in a given year is simply the sum of the amount caught by each technology within a given year.

$$H_t = H_{s1,\, tech1} + H_{s1,\, tech2} + \ldots + H_{s1,\, techn}$$

3.3 Fishery-wide revenues, costs, and profits

Revenues are calculated per species as the product of the species' price *p* by the species' *s* harvest *H* in period *t*.

$$revenue_{s1} = p_{s1} H_{s1}$$

We assume each unit of fish is sold for its full price, regardless of how it is caught. Fishery-wide revenue is the sum of the species-specific revenues.

$$\textit{Fishery-wide revenue} = p_{s1} H_{s1} + p_{s2} H_{s2} + \ldots + p_{sn} H_{sn}$$

Since fishers apply their effort through technologies, unlike revenue, fishery costs are calculated per effort per technology. The cost of fishing per technology in a given year is the technology's cost per unit effort, *c* multiplied by the square of the effort applied to that technology, *E*.

$$cost = c \times E^2$$

We square our cost term so that costs increase with increasing effort as this is more representative of real-world fishing dynamics, and prevents corner solutions in our model. The power of two was chosen since there are several examples in the literature of non-linear costs simulated with similar exponents (Charles, 1985). The cumulative cost of fishing for a given year is simply the sum of the costs across all technologies.

$$C_t = c_{tech1} E_{tech1}^2 + c_{tech2} E_{tech2}^2 + \ldots + c_{techn} E_{techn}^2$$

Fishery-wide profits are calculated by subtracting fishery-wide revenues from fishery-wide costs.

$$profit = revenues - costs$$

3.4 Optimization of effort allocation and determining baskets caps

To simulate fishing dynamics, we assume fishers will allocate effort to the technology combination that maximizes profit within a given year. So, for any given year, a new optimal set of efforts is calculated and applied. Note that we assume myopic optimization: profits are only maximized within a given year (not for several periods).

We employ the quadratic programming method (Goldfarb & Idnani, 1982; 1983) to maximize profits according to a combination of efforts in a given year by minimizing the derivative of a matrix equation for profits (the objective function, Equation 1) subject to two constraints: (i) a harvest must not exceed a predetermined limit, and (ii) effort must be nonnegative.

$$\min \frac{1}{2} E^{'} D E - d^{'} E \qquad subject\ to: AE \geq b$$

$$E \geq 0 \qquad Equation\ 1$$

$$d^{'} = P^{'} B Z$$

Equation 2

where,

s: species
i: technologies
k: number of baskets
d: i×1 vector of revenues
D: i×i matrix of technology costs
E: i×1 vector of the fishing effort of all technologies
b: k×1 vector for quota basket caps
A: k×i matrix of harvest of each species
B: s×s matrix of stocks
P: s×1 vector of prices
Z: k×i matrix of catchability of each species using available technologies

The off-diagonal elements of the technology cost matrix, *D*, stock matrix *B,* and catchability matrix *Z* are all zero. The i^{th}diagonal element of matrix *D* is $D_{i*i} = 2c_i$, where *c* is the cost parameter for i^{th} technology. Matrix *B* has s^{th}diagonal elements of $B_{s*s} = X_s$, where *X* is the stock for species *s*. And matrix *Z* has the $s * i^{th}$element of q_{s*i}, which is the catchability of species *s* using technology *i.*

Revenue's vector *d* is the price vector *P,* multiplied by matrix *B* and matrix *Z* (Equation 2). Revenue's vector *d has a dimension* $i * 1$.

3.4.1. Implementing basket constraints

For our first constraint, we confine our efforts to nonnegative values by inserting zeros into each t^{th}element of vector j.

Our second constraint adds quota basket dynamics into our model by grouping species into baskets using a binary matrix, *M*, indicating whether or not a species is contained in a basket. The $k * s^{th}$ element ofM_{k*s} is 1 if quota basket k contains species s, otherwise it is 0. Species can only be in one basket, and each basket must contain at least one species.

Matrix *A* is the negative of matrix *M* multiplied by, matrix *B,* and matrix *Z*. We can read $k * i^{th}$ element ofA_{k*i}as the negative harvest per unit effort using technology i in quota basket k.

$$A = -MBZ$$

where,

Z: k×i matrix of harvest of each species

We incorporate harvest limits for each basket into our model as a second constraint under our quadratic programming optimization. Each year's allowable harvest is calculated as a fixed percentage *m* of the combined standing stock of all the species within that basket.

$$Harvest\ Limit = m * (X_{s1} + X_{s2} + ...X_{sn})$$

This allows the actual harvest of each basket to change dynamically each year in response to changing stock abundance, similar to how yearly quotas are set for many fisheries. Quota basket vector *b* consists of the negatives of these caps for each k^{th} quota basket.

3.4.2 Implementing basket constraints and determining baskets caps

Quadratic optimization was conducted using the quadprog() package in rStudio (Goldfarb & Idnani, 1982; 1983; quadprog version 1.5-8, Turlach port by Weingessel, 2019).

We compare quota baskets to global and single-species management on the basis of profit maximization. Thus, in each scenario, caps are set to maximize fishery-wide profits.

To determine which caps return the highest net profits for the length of the time period considered, we use a modified BFGS quasi-Newton optimization scheme applied through the optim() package in rStudio (Byrd et al., 1994; optim version 4.02, R Core Team, 2020). In short, this optimizes the cap for each quota basket so that net profits are maximized over the model run time period (always 30 years for our scenarios) by adjusting the effort applied to each technology (calculated using quadratic programming, detailed above).

3.5 Analysis scenarios

3.5.1 Testing quota basket theory

To test how quota baskets compare to each other, single-species management, and global quotas, all possible combinations for 2, 3, and 4 baskets for a hypothetical five-species fishery were calculated to form a binary matrix, *M*. The combinations in matrix *M* were calculated by finding all unique binary permutations of a five column, two, three, or four row matrix.

Basket caps (constant percentages) were calculated to maximize fishery-wide, 30-year net profits as described in section 3.4 above. Parameters for each species and technology were kept constant and are found in (Tables 4 and 5). All technology costs per unit of effort are $ 1.

Table 4: Species parameters for analyzing every basket combination

Species	r	K	Starting stock	Price
1	0.15	100	50	10
2	0.2	100	50	20
3	0.2	100	50	8
4	0.3	100	50	10
5	0.4	100	850	12

Table 5: Technology matrix for analyzing every basket combination

Technology	Species 1	Species 2	Species 3	Species 4	Species 5
1	0.04	0.01	0.01	0.01	0.01
2	0.01	0.04	0.01	0.01	0.01
3	0.01	0.01	0.04	0.01	0.01
4	0.01	0.01	0.01	0.04	0.01
5	0.01	0.01	0.01	0.01	0.04

Global and single-species management scenarios were calculated by running our model after grouping species into one (global) or five (single-species) baskets, respectively.

To illustrate the effects different basket combinations have on fishery profits, we compared fishery profits summed over the 30-year period with no discounting for each basket combination. To show the effects on standing stock biomass, we compared the biomass in year 30 for each species under every basket combination.

3.5.2. Testing grouping hypotheses

To test how grouping species by different attributes affects fishery outcomes, we analyzed a five-species, two-basket fishery under three different basket groupings. Basket caps (constant percentages) were calculated to maximize fishery-wide, 30-year net profits as described in section 3.4 above. The technology matrix, *Z* was kept constant for each scenario as in Table 5, and all their costs are $1. Input parameters were varied only for the grouping variable, and otherwise kept constant. Baskets were defined by species' intrinsic growth rate, *r*, carrying capacity, *K*, or profit (the difference between price and cost). Input parameters for these grouping scenarios are found in Table 6.

Each scenario consisted of three different basket groupings of species having either a high or low trait for each attribute.

Attribute traits

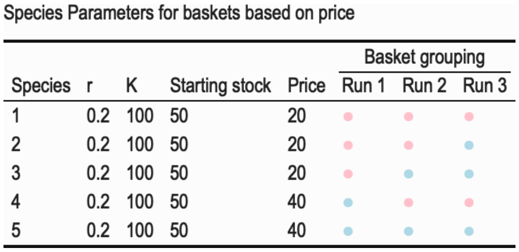
1. Profit: high trait price is $40, and low trait price is $20.
2. Intrinsic growth rate: high trait rate is 0.4, and low trait rate is 0.2.
3. Carrying capacity: high trait capacity is 300 tons, and low trait capacity is 100 tons.

Scenario groupings

A. **Similar (Run 1)**- similar species grouped together (low basket: 3 low trait species, high basket: 2 high trait species),
B. **Somewhat Different (Run 2)-** some different and some similar species grouped together (high basket: 2 high trait, 1 low trait species; low basket: 2 low trait species), and
C. **Very Different (Run 3)-** mostly different species grouped together (low basket: 2 low trait, 1 high trait species; balanced basket: 1 low trait, 1 high trait species)

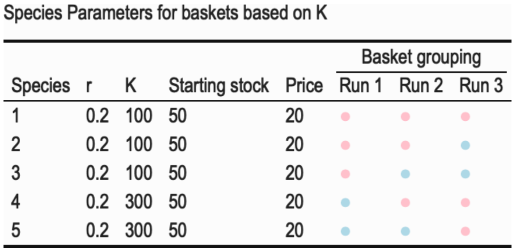
Basket combinations are found in the basket groupings column of Table 6. The colors denote if the species share the same basket in each scenario run.

Table 6: Species parameters for analyzing groupings



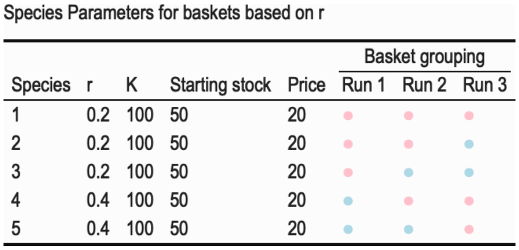
Species Parameters for baskets based on price

Species	r	K	Starting stock	Price	Basket grouping Run 1	Run 2	Run 3
1	0.2	100	50	20	🔴	🔴	🔴
2	0.2	100	50	20	🔴	🔴	🔵
3	0.2	100	50	20	🔴	🔵	🔵
4	0.2	100	50	40	🔵	🔴	🔴
5	0.2	100	50	40	🔵	🔵	🔵



Species Parameters for baskets based on K

Species	r	K	Starting stock	Price	Basket grouping Run 1	Run 2	Run 3
1	0.2	100	50	20	🔴	🔴	🔴
2	0.2	100	50	20	🔴	🔴	🔵
3	0.2	100	50	20	🔴	🔵	🔵
4	0.2	300	50	20	🔵	🔴	🔴
5	0.2	300	50	20	🔵	🔵	🔴



Species Parameters for baskets based on r

Species	r	K	Starting stock	Price	Basket grouping Run 1	Run 2	Run 3
1	0.2	100	50	20	🔴	🔴	🔴
2	0.2	100	50	20	🔴	🔴	🔵
3	0.2	100	50	20	🔴	🔵	🔵
4	0.4	100	50	20	🔵	🔴	🔴
5	0.4	100	50	20	🔵	🔵	🔴

We validate the profit results for each basket arrangement by varying the variables of each low trait species. In this way, we test if the outcomes change when the likeness among species traits increases.

Varying attributes

1. Profit: low-trait prices go from \$2 to \$40 (step 2).
2. Intrinsic growth rate: low-trait rates go from 0.02 to 0.4 (step 0.02).
3. Carrying capacity: low-trait capacities go from 100 tons to 300 tons (step 10).

3.5.3 Price and cost scenarios

To test how different species prices and technology costs affect basket outcomes, we analyzed a four-species, two-basket fishery with either different prices or costs under several optimal basket groupings compared to a control of uniform prices and/or costs. The combinations in binary matrix *M* were calculated by finding all unique binary permutations of a four column, two row matrix. Two scenarios were tested for prices and two for costs.

For prices, Scenario A tested the effects of a single high-priced species within a differentiated fishery, while scenario B tested the effects of two possible prices. For costs, Scenario A tested the effects of a single high-cost technology within a differentiated fishery, while scenario B tested the effects of two possible technology costs and two possible intrinsic growth rates. For both the price and cost scenarios, technologies were not perfectly selective (see catchability matrix in Table 5). Basket caps (constant percentages) were calculated to maximize fishery-wide, 30-year net profits as described in section 3.4 above. Input parameters were varied according to Tables 7 and 8.

Table 7: Parameters for the price scenario

				Scenario A		Scenario B	
Species	**K**	**X**	**c**	**p**	**r**	**p**	**r**
1	100	50	1	Either 1 or 40	0.15	Either 20 or 30	0.15
2	100	50	1	Either 1 or 40	0.2	Either 20 or 30	0.2
3	100	50	1	Either 1 or 40	0.3	Either 20 or 30	0.3
4	100	50	1	Either 1 or 40	0.4	Either 20 or 30	0.4

Table 8: Parameters for the cost scenario

				Scenario A		Scenario B	
Species	**K**	**X**	**p**	**c**	**r**	**c**	**r**
1	100	50	20	Either 1 or 2	0.15	Either 1 or 2	0.2
2	100	50	20	Either 1 or 2	0.2	Either 1 or 2	0.2
3	100	50	20	Either 1 or 2	0.3	Either 1 or 2	0.3
4	100	50	20	Either 1 or 2	0.4	Either 1 or 2	0.3

Results

Testing quota basket theory

We hypothesized that a fishery managed with two or more quota baskets will outperform a global quota, in terms of fishery profits; and that single species management (when each species has its own quota) will outperform quota baskets. We also hypothesized that implementing quota baskets can achieve specific fishery objectives by shifting fishing effort. We tested these hypotheses by comparing the total fishery-wide profits and year-30 biomass levels for fisheries managed with all possible profit-maximizing (referred to as ‘optimal’) arrangements of 1-5 quota baskets.

Well-designed baskets improve fishery profits compared to a global quota

This comparison shows that the optimal two, three, and four basket groupings improve upon global management, with each of these being, respectively, \$915.83, \$1,344.37, and \$1,353.89 more profitable than the global quota (Figure 2). These differences between optimal quota baskets and a global quota also reveal decreasing marginal returns. While increasing the number of baskets from one to two results in a 9.2% improvement in profits, increasing from four to five baskets only yields a mere 0.07% improvement. Thus, as the number of baskets increases, the marginal benefit of an additional basket declines. The profits returned by the four basket scheme are virtually identical to that of five baskets (single-species management). Therefore, although a well-designed quota basket scheme can outperform global management, well-designed does not necessarily imply high-complexity. Simple quota basket schemes may be sufficient to meet management goals.

Poorly designed baskets can reduce fishery profits compared to a global quota

Our results also indicate that it is possible for quota baskets to underperform compared to global quotas. Specifically, two different 2-basket combinations produce profits that are, respectively, \$320.30 and \$446.57 below the profits delivered by a global quota (Figure 2). Thus, while quota baskets can improve profits for a fishery, they are not guaranteed to be better than a global quota. This underscores the importance of choosing an appropriate scheme during the planning stage.

Basket design is more important than basket number

Furthermore, our results show that increasing the number of baskets does not always result in higher profits in our hypothetical fishery (Figure 2). In fact, there are 20 combinations of 3-basket schemes that perform worse than the best 2-basket scheme, and 17 combinations of 4-basket schemes that perform worse than the best 3-basket scheme. Thus, basket design is a far more important determinant of fishery outcomes than the number of baskets.

Basket design directs fishing pressure towards certain species

A comparison of year-30 biomass levels per species reveals a wide range of potential biomasses under optimal two, three, and four basket schemes (Figure 3). For example, the potential year-30 biomasses for species four ranges from ~22 to ~79 tons (r = 0.3). Thus, for some combinations, targeting species 4 is essential to maximize profits, leading to low year-30 biomasses for species four. In other combinations, species four is barely targeted, leading to high year-30 biomasses. Furthermore, our results also demonstrate that it is possible for biomass to be lower under quota baskets than it would be under single species management and even under a global quota. For example in our hypothetical fishery, there are 13 two-basket combinations where species two has a lower biomass than it would have under a global quota (Figure 3), and only 2 where it exceeds the global quota. The two high-biomass combinations place species two in either an individual basket (second-highest species two biomass), or only with species one, the slowest-growing species (highest species two biomass). In these combinations, the quotas on the basket containing species two are the lowest two possible because the quota is based on the overall growth rate of the basket. By itself, the species two basket grows at species two's rate. When combined with species one, the basket overall grows even slower, but species one satisfies some of the basket quota. Thus, due to the inclusion of species one, the basket quota is slightly higher, yet still allows species two biomass to accumulate beyond that found in an individual basket.

Furthermore, most species' year-30 biomass levels are highest under the optimal arrangements. For example, under the best-performing 2-basket combination, the biomass levels of all the species exceeds that under the global quota; and under the optimal 3-basket combination, only

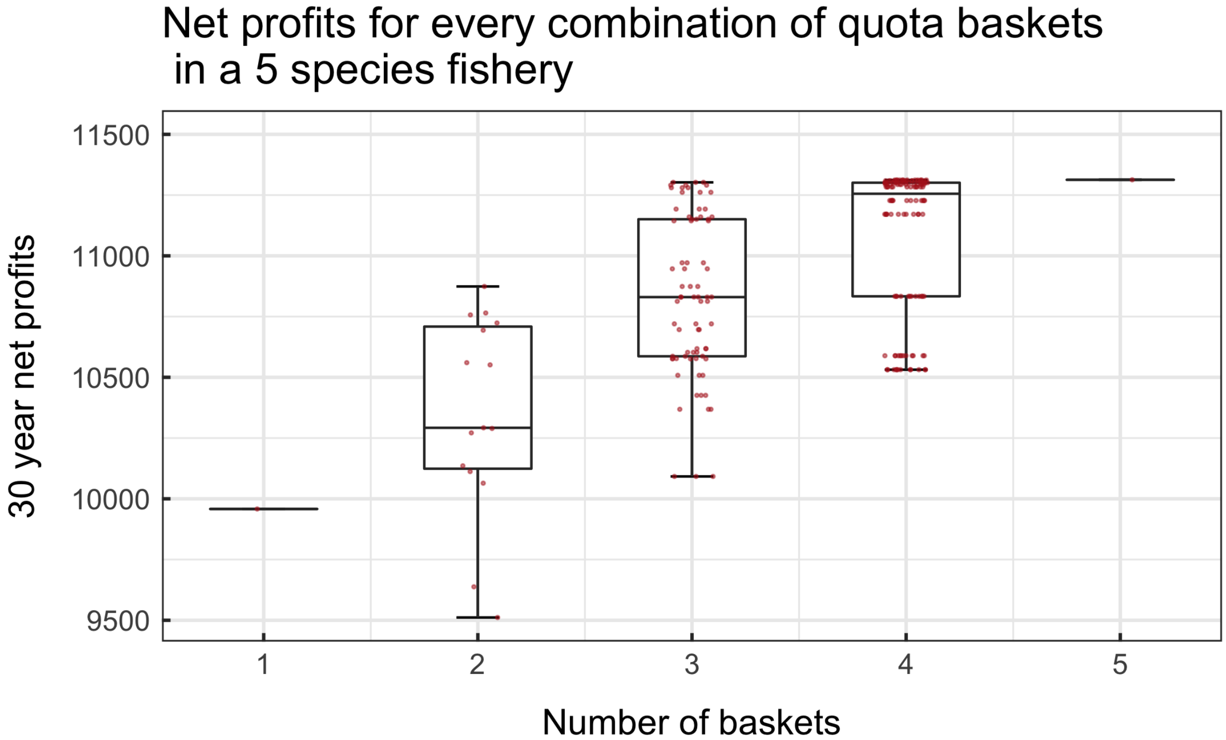


Figure 2: Net profits for every combination of quota baskets in a 5 species fishery. *Boxplot of 30-year net profit distributions for every basket combination in a 5 species fishery. Fishery parameters are found in Table 4. Basket profits are determined for each basket combination by optimizing our model harvest limits to return the maximum profits for 30 years. There is only one optimal arrangement for one basket (all species in the same basket) and 5 baskets (all species in individual baskets). Increasing basket numbers can, but does not necessarily, lead to improved fishery profits over a thirty year period.*

species three has a biomass level markedly lower than it is under the global quota. It is important to note that all of these optimal arrangements hold biomass levels below the MSY of 50 units. However, while the maximized global quota does allow some species above MSY, this is only at the expense of severely over-fishing other species. These results show that different basket combinations can shift fishing effort to result in different standing stock biomass levels depending on which species are grouped together within a basket.

Biomass outcomes converge to single species management as more baskets are added

Since quota baskets apply a single quota to multiple, diverse species, the optimal quota for a basket should lie somewhere between the optimal quota for each species individually. Thus, we expect that as the number of baskets within a fishery increases, the species biomass levels should approach those under single species management. Our year-30 biomass results show that for some species (i.e. species one, three, and four), biomasses decrease with the addition of baskets, while for others (i.e. species two and five), biomasses increase (Figure 3). These decreases/increases ultimately lead to a convergence on the global quota biomass levels. Thus, as the number of baskets is increased, the year-30 biomasses for each species approaches the single species management biomasses.

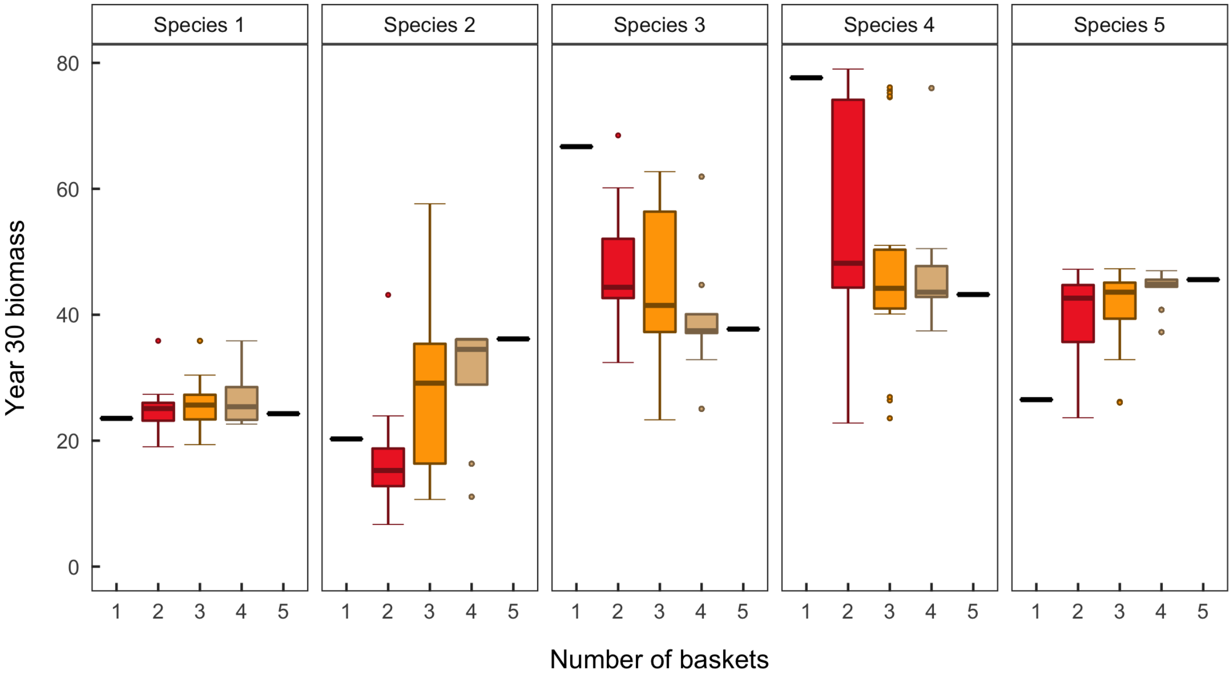


Figure 3: Boxplot of year-30 biomasses for each species for every basket combination in a 5 species fishery. *Boxplots of the potential biomass outcomes for each species in a 5 species fishery for every combination of quota baskets for the same analysis in Figure 3.*

Testing grouping hypotheses

To explore how grouping species by different traits affects fishery outcomes, we analyzed a five-species, two-basket fishery under three different basket groupings: one where each basket contains identical fish ("All Same"), one where baskets are composed of mostly similar fish ("Somewhat Different"), and one where baskets contain very different fish ("Very Different").

Similar baskets generally improve profits

Our comparison of species groupings by traits illustrates that baskets containing species with similar traits generally maximize fishery-wide profits (Figure 4). In contrast, baskets where species have highly variable traits tend to perform worse (with the exception of intrinsic growth rate (r), discussed later). These results highlight how grouping similar species into baskets usually, but not always, maximizes fishery-wide profits.

Grouping species with different traits can lead to low biomasses

Our comparison of species groupings by traits also indicates that baskets containing species with similar traits tend to have high fishery-wide biomass (Figure 5 and 6). When species only differ in their respective carrying capacities, biomass levels do not shift much in response to different

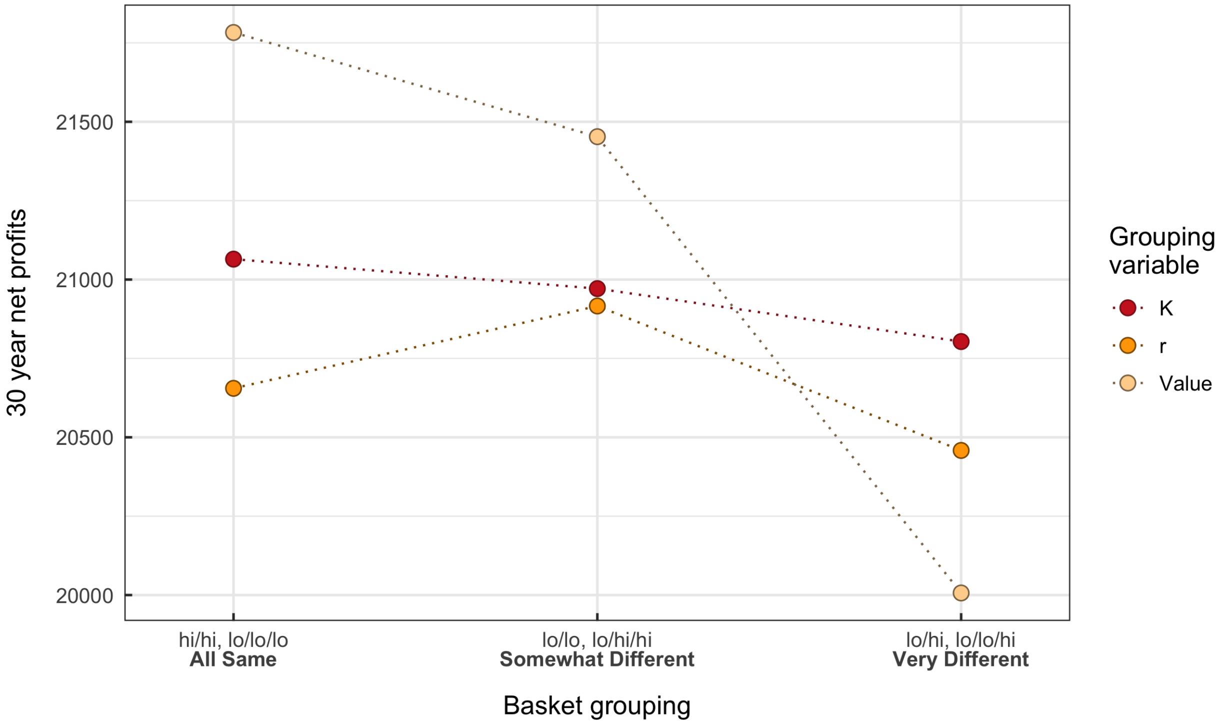


Figure 4: Net profits for 3 distinct basket arrangements by trait. *Profit outcomes for a five species fishery where two fish have high carrying capacities, r values, or profits (price-cost). Profit outcomes are calculated as the net profits from a 30 year run of our quota basket model with three distinct basket groupings: "All Same", where high trait species and low trait species are grouped separately; "Somewhat different", where one basket contains two low trait species and the other contains two high and one low trait species; and "Very different", were one basket contains a high and low trait species and the other contains two low and one high trait species. Parameters are found in Table 6.*

basket groupings. However, with respect to intrinsic growth rate and profit, similar groupings tend to result in stable biomasses. In contrast, grouping highly variable species together increased fishing pressure on some species, yielding low fishery-wide biomasses. These results show that baskets containing similar species usually result in high standing biomass for a fishery.

Fishers prioritize high growth species first

Much of the results of our species groupings by trait comparison can be attributed to a particular phenomenon: optimal profits are achieved by targeting species that yield high returns. Since the returns of a species depend on the quantity harvested, it is optimal to target high-growth species. This is illustrated by the different biomass and harvest rates of the "All Same", "Somewhat Different", and "Very Different" combinations based on intrinsic growth rate (r). In these combinations, the fast-growing fish (species 4 and 5) are targeted, sometimes to the detriment of the other species (Figure 5). The interplay between this targeting of fast-growing species, and the caps on the two baskets produces the revealing exception to the trend mentioned earlier that similar baskets maximize profits. In our hypothetical fishery, the "Somewhat Different" combination grouped by r produces higher profits than the "All Same" combination. This result

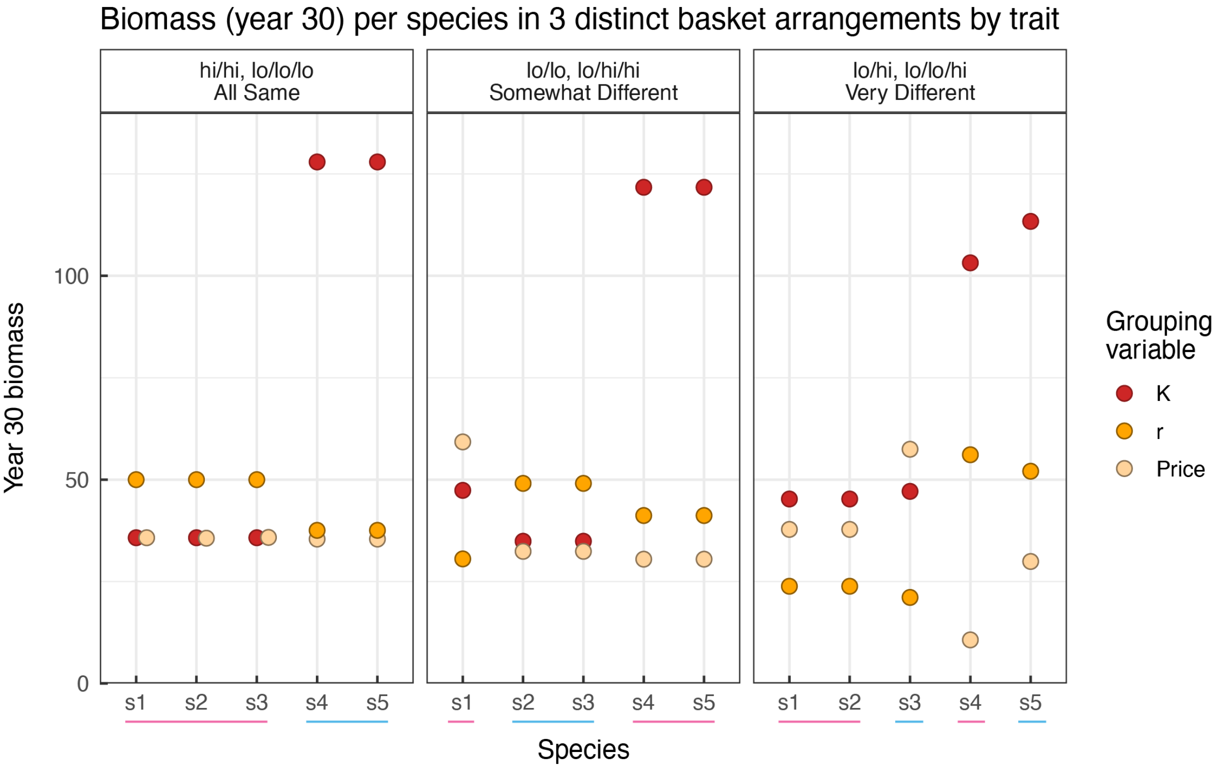


*Figure 5. **Year 30 biomasses for all five species in three distinct basket groupings arranged by trait.** Biomass outcomes for a five species fishery where two fish have high carrying capacities, r values, or prices. Biomass outcomes are calculated as the year 30 biomass from a 30 year run of our quota basket model with three distinct basket groupings: "All Same", where high trait species and low trait species are grouped separately; "Somewhat different", where one basket contains two low trait species and the other contains two high and one low trait species; and "Very different", were one basket contains a high and low trait species and the other contains two low and one high trait species. Parameters are found in Table 6. Species 4 and 5 are always high trait species, species 1, 2, and 3 are always low trait. Baskets are indicated by the colored lines under each species name, where the same colors indicate that species are in the same basket.*

echoes that found during the comparison of the 1-5 quota basket combinations discussed earlier (Figure 2). Here we find that it is best, in terms of profits, to group one slow-growth species with two high-growth species because it is optimal to harvest high-growth species as much as possible. For the “Somewhat Different” combination, grouping a slow-growth species with the high-growth species results in an initially higher harvest rate for that slow-growth species than when it is grouped with other slow-growth species (Figure 6). This initial higher harvest results in higher total profits for the “Somewhat Different” combination over the 30-year period compared to the “All Same” combination. However, since this initial high harvest rate is short-lived, the marginal profit benefit of grouping a slow-growth species with high-growth species rapidly diminishes over time. Similarly, the results for the “Very Different” combination are also the consequence of targeting high-growth species. Since there is one high-growth species in each basket in the “Very Different” combination, the optimal quotas for both baskets are quite similar, slightly favoring the two-species basket simply because the overall growth rate of this basket is higher than that of the three-species basket.

Overall, our analysis reveals that generally more baskets improves fishery outcomes but with declining marginal returns, but increasing the number of baskets does not guarantee improvement. Thus, the composition of baskets is far more important than the number of baskets. Regarding basket composition, profits are optimal when: (i) species with similar traits are grouped together, and (ii) quotas are set to maximize the extraction of quick-growth species. These two phenomena sometimes do not align (as in the case of intrinsic growth rate), and often profit maximization occurs at the expense of standing biomass. Thus, while grouping fish with similar traits is a good starting point for basket construction, other groupings may actually be optimal.

Price and Cost Scenarios

The previous section began investigating the role that prices and costs could play in quota baskets by considering the value (profits) of a species. To explore the role of price further, a control of uniform prices was run along with all possible combinations of two additional 4-species scenarios: a) One high-priced and three low-priced species; and b) Two high-priced and two low-priced species. In both scenarios, each species could have one of four possible intrinsic growth rates. Similarly, to explore the role of costs further, a control of uniform costs was run along with all possible combinations of two additional 4-species scenarios: a) One high-cost and three low-cost technologies; and b) Two high-cost and two low-cost technologies. Although technologies were not perfectly selective, each technology was markedly more well-suited to catching only one of the four species. So, aside from minor bycatch, each technology was effectively catching its respective species (i.e. technology 1 catches predominantly species 1). In scenario A, each species could have one of four possible intrinsic growth rates, while in scenario B, species could have either of two possible intrinsic growth rates.

Profits are optimized by targeting higher-value species.

The result of the price and cost scenarios revealed that targeting high-value species is optimal. This trend is visible in the exploration of the marginal benefit of increasing the number of baskets in a fishery in the results of species 2 and species 3 are compared in the every basket scenario (Figure 3). Identical except for their prices (price species 2 > price species 3), on average species 2 has a lower year-30 biomass than species 3. This trend is most clearly seen in scenario A of our price and cost explorations. In price scenario A, the annual biomass of the high priced stock was always lower than it would have been under uniform prices. Since raising the cost of catching a certain species is quite similar to lowering the price that species fetch, this trend of seeking high-value species was echoed in the cost scenarios. In cost scenario A, the annual biomass of the stock targeted by the high cost technology was always higher than it would have been under uniform costs. This trend persisted in scenario B, too, even when there were only two different growth rates, not four.

Profits are optimized by targeting faster-growing species.

This trend was demonstrated in the grouping analysis in Figures 4 and 5, as well as the B scenarios for price and cost. When slow-growing species have a higher cost (or a lower price),

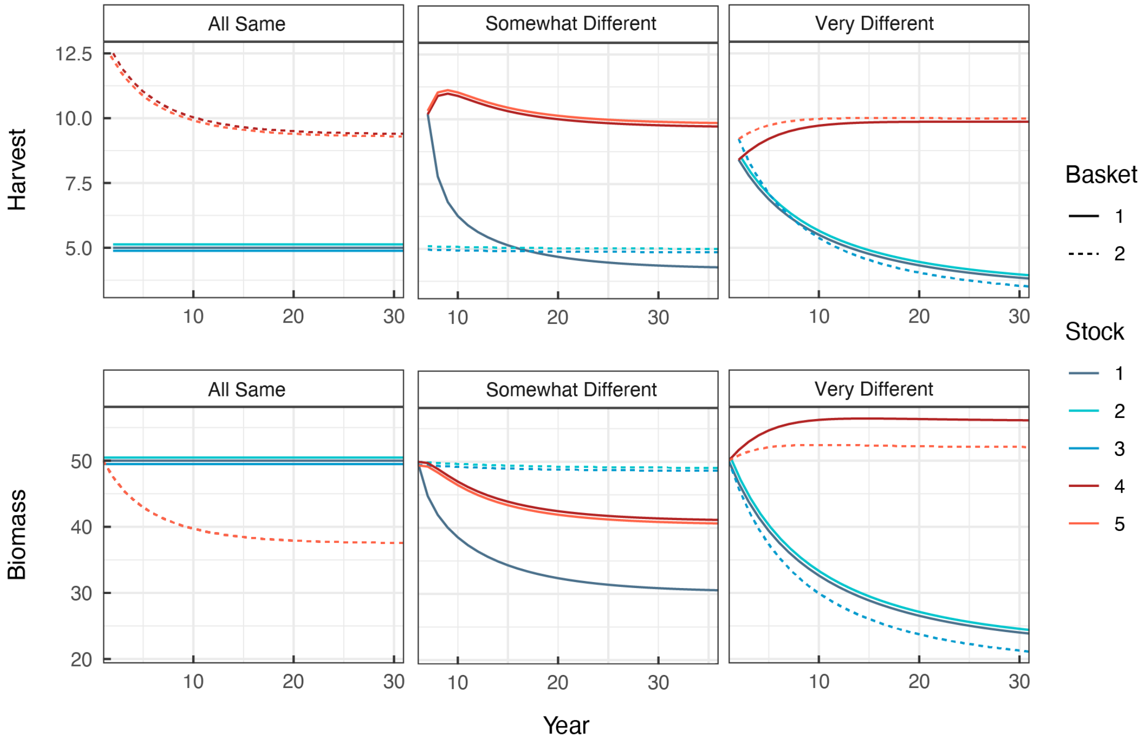


__Figure 6. Biomasses and harvest for all five species in three distinct basket groupings arranged by intrinsic growth.__ Harvest (first row), and biomass (second row) outcomes for a five species fishery. Biomass outcomes are calculated each year for our quota basket model with three distinct basket groupings: "All Same", where high trait species and low trait species are grouped separately; "Somewhat different", where one basket contains two low trait species and the other contains two high and one low trait species; and "Very different", were one basket contains a high and low trait species and the other contains two low and one high trait species. Parameters are found in Tables 6. Species 4 and 5 are always fast growth species, species 1, 2, and 3 are always slow growth. Parallel lines indicate two species have the same harvest or biomass trajectory. Baskets are indicated by dashed or solid lines, and species are indicated by color ,where high growth species are reds and low growth species are blues.

their annual biomass is higher than it would be with uniform costs (or prices). The changes hold true no matter if there are four different growth rates in play or just two.

Biomass levels can vary dramatically depending on the particular species combinations across baskets

The interplay between targeting fast-growing and high-priced species can produce dramatically different biomass levels. This is demonstrated by the comparison of trait groupings in Figures 4 and 5. In this comparison, the “Very Different” combination produces the worst outcome in both profits and biomass (Figure 7). In the basket with two low-value species and one high-value species, harvest is concentrated on the most profitable species (species 4), quickly depleting its biomass. The extraction of the low-value species increases initially, then gradually declines over time simultaneous to the dramatic descent of species 4. This initial increase followed by a gradual decrease seen in the two low-value species occurs because fishing pressure shifts from the high-value species and on to the low-value species as the high value-species becomes less abundant. At the same time, in the other basket, the smooth decline of the high value species is mirrored by the growth of the low-value species. Across both baskets, as the high-value species becomes less abundant, there is less opportunity for profit, and thus, fishery-wide profits follow total biomass, and decline over time.

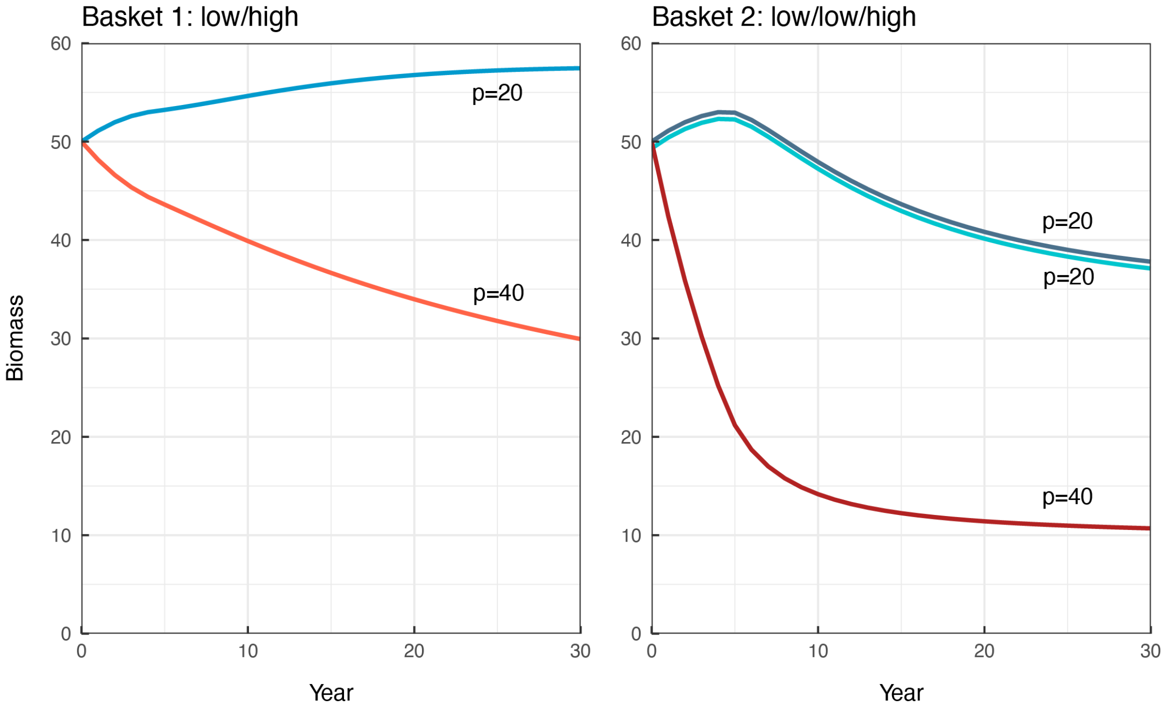


Figure 7. Biomasses for all five species in two distinct basket groupings arranged by profit. *Biomass outcomes for a five species fishery where two fish have high prices (p=40, c=1, red colors), and three have low prices (p=20, c=1, blue colors). Biomass outcomes are calculated for each year for the “Very different” basket, where one basket contains a high and low trait species and the other contains two low and one high trait species. Parameters are found in Table 6. Parallel lines indicate two species have the same biomass trajectory.*

The “best” basket changes as fishery parameters change

To see different basket species parameters change the relative outcomes of different basket arrangements, we compared the total 30 year net profits of our “All Same”, “Somewhat different”, and “Very different” baskets over a range of intrinsic growth rates for the low growth rate species (Figure 8). Changing the intrinsic growth shows that the best basket, in terms of profit, changes depending on the species parameters. The "All same" basket consistently provides high profits, and is the best basket when the species intrinsic growth difference is small (high r in Figure 8). In contrast, the "Somewhat different" basket is the best basket arrangement when traits differences are bigger (lower r in Figure 8). This finding reinforces that quota basket management is best when the target fishery and its biology are well understood.

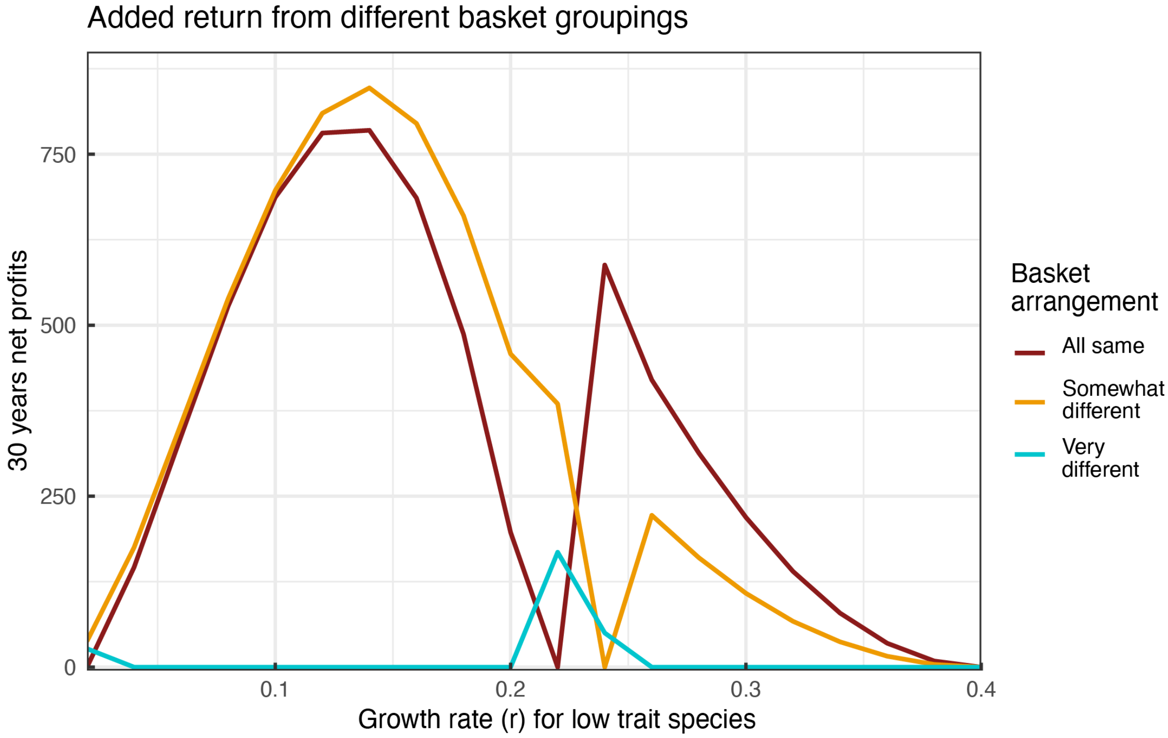


Figure 8: Added return for 3 distinct basket arrangements over the basket with the lowest profit for changing intrinsic growth rates. *Profit outcomes for a five species fishery with three low r species and two high r species (r = 0.4), where the r values for the low r species range from 0-0.4, with a 0.2 step. Profit outcomes are calculated as the net profits from a 30 year run of our quota basket model with three distinct basket groupings: "All Same", where high trait species and low trait species are grouped separately; "Somewhat different", where one basket contains two low trait species and the other contains two high and one low trait species; and "Very different", were one basket contains a high and low trait species, and the other contains two low and one high trait species. This graph shows the added return from each basket, or each basket's profit outcome minus the lowest performing basket for each growth rate.*

Case Studies

The quota basket approach is a reframing of several fisheries management tactics, rather than a truly novel method. As such, certain fisheries have implemented quota basket schemes that are simply referred to by other names. In this section, we analyze two similar fisheries, one managed by a quota basket and the other managed without. The first is the Pacific Groundfish fishery, a large multispecies fishery where many stocks collapsed despite relatively involved management., We then examine the Bering Sea and Aleutian Islands groundfish fishery, where a two-million ton "quota basket" has prevented overfishing and significant stock decline for thirty years.

The Pacific Groundfish fishery and the Bering Sea Groundfish fishery are both mixed species fisheries with high spatial, fishing intensity, species level, and genus level variability, as well as significant variation in the amount each species has been studied. Both fisheries contain high-value fish that bear the brunt of the region's fishing pressure - Pacific Whiting in the Pacific Groundfish fishery, and Pollack in the Bering Sea fishery - but also contain many rockfishes, elasmobranchs, flatfishes, etc. (NPFMC, 2015; PFMC, 2016). However, their original management differed: the Pacific fishery set mostly single species harvest levels, while a two million ton total harvest cap supplemented single species limits in the Bering Sea fishery (Clark, 1991; NPFMSC, 2015; NMFS, 2020).

The quota harvest limits set on the Pacific Groundfish fishery failed. In 1998, a survey of several groundfish species showed significant overfishing and continued population declines with no foreseeable trajectory to reach equilibrium harvest at the then-current mortality levels (Ralston, 1998). The fixed constant mortality chosen to achieve $F_{mmy} = 35\%$ for the fishery was still too much fishing for some "weak stock" species to handle. In addition to significant biomass declines in "weak stocks", the quota basket approach also significantly impacted fishery revenues. After declining stocks lead to diminished harvest, the extremely low harvest limits exacerbated the revenue loss across the fishery. Thus, due to overexploitation and ultimately collapse, fishery-wide revenues in 2000 declined to half of what they were in 1982 (Warlick, 2018).

The Bering Sea Groundfish, however, has seen thirty years of sustainable harvest under a quota basket (PFMC, 2016). A two million ton quota is a relatively conservative quota for the fishery, and historical fishing has only occasionally exceeded 2 million tons (Witherell et al., 2000; PFMC, 2016). In fact, the two million ton cap is well below the sum harvest if each species was fished at 80% of maximum sustainable yield (Witherell et al., 2000; DiCosimo et al., 2010; Melnychuk et al., 2013). A key factor in the success of the Bering Sea Groundfish fishery is that the species involved occupy a wide range of market demand, where pollack fetch a much higher price and have a much larger market than other species (PFMC, 2016). As a result, the majority of the fishing effort in the Bering Sea is put towards pollack, and pollack catches fill over half of the quota (PFMC, 2016). Pollack can handle this level of fishing pressure, and the remaining quota is split between all of the other species in the fishery. The relatively limited remaining quota keeps fishing pressure on all the other species low, maintaining a sustainable fishery.

Comparing these two fisheries leads to a few important conclusions about quota baskets. The first is that fishers will fish beyond maximum sustainable yield when left to their own devices, and quota baskets can help limit this tendency to overfish. Overexplotation of stocks is a well known consequence of open access fisheries, (Bjorndal & Conrad, 1987) but potentially less clear under a generous multispecies quota. In the Bering Sea, we see a quota basket prevent overfishing of weak stocks by directing fishing pressure towards high value pollack. In the

Pacific Groundfish fishery, the lack of a global quota allowed fishers to target groundfish beyond sustainable levels despite a similar high value fish, Pacific Whiting, existing in the fishery. Here, a simple global harvest quota drastically changed fishing outcomes in the Bering Sea.

The second is that a quota basket design is more important than quota basket number. Quota baskets can help prevent collapse, but their success highly depends on their design. In the Pacific Groundfish fishery, species declines were mainly caused because single species harvest limits were set too high. However, a single additional global quota led to stable fisheries in the Bering Sea. This result, that quota basket design is more important than number, is reflected in our modeling, where we show that good basket design improves fishery profits, but poor basket design can perform worse than a global quota (Figure 2).

The last conclusion we can draw from these case studies is that the success of any quota basket design depends on how the quota and resulting fishing pressure interacts with the species involved. A major reason that the Bering Sea quota basket succeeded is because pollack drew fishing pressure away from other species under a low harvest limit. Without pollack or with a higher cap, this basket may have led to overfishing of weak stocks, as in the Pacific Groundfish fishery. These case studies reinforce the idea that a clear understanding of the target fishery is very important to designing a good quota basket scheme.

Discussion

Every fisheries management scheme must compromise some objectives in pursuit of others, and quota basket management is no exception. Research suggests that some management goals are incompatible (Andersen et al. 2015), but some avoidable trade offs exist (Jacobsen, Burgess, & Andersen, 2017). Though we used a profit-maximization approach, quota baskets showed the potential to achieve stable stocks and good profits over time by grouping fish with similar or different characteristics. However, not all groupings are successful, and we can identify some recommendations that may avoid poor fishery outcomes.

Quota baskets are designed with a clear goal in mind.

A manager will only apply a new management strategy to a fishery if the status quo fishing does not achieve the manager's goals. Quota baskets, then, will improve on status quo fishing if they are designed with a specific goal in mind. Our model results show that well designed baskets improve fishery profits, but poorly designed baskets sacrifice profits compared to global management and lead to low biomass outcomes (Figures 2, 3, 4, 5). A major benefit to quota baskets is that the multitude of potential basket groupings allows baskets tailor made to achieve a certain result. Our results show that for profit maximization goals, quota baskets can improve upon simpler management schemes. We believe that this result is true for any target goal: a well designed quota basket scheme can improve fishery outcomes for many goals. However, the many basket options also leaves many baskets that hinder fishery outcomes. Choosing the best quota basket design for a particular situation depends on having a clear fishery outcome in mind.

A quota basket has a clear mechanism to achieve that goal.

The dynamics of a fishery under any quota basket scheme are complex, entwining fisheries biology, market forces, and fisher's behavior. While it is near impossible to predict every consequence of a quota basket, a manager should put significant effort into understanding how a quota basket achieves its goal for a specific fishery. In our model, fishery outcomes are a direct result of fishers targeting high value species (Figure 5, 6). As such, we can build quota baskets that leverage fishers targeting behavior to improve fisheries outcomes and avoid poorly constructed baskets (Figure 3). As proof that this concept translates to the real world, our Bering Sea case study shows how a single quota can influence fishers targeting behavior to protect weak stocks in the fishery.

While we focus on price and targeting behavior, fisheries dynamics are complex, entwining ecology, market influences, social dynamics, and more that all determine how a quota basket will affect a fishery outcome. Different basket constructions will result in very different fishery outcomes. This provides a great opportunity: China has managed to bolster food production through ecosystem manipulation in their fisheries (Szuwalski et al., 2017). However, predicting the dynamics of a quota basket must be done in a fishery specific way. Because each fishery is unique, with varied stakeholders, fishing gears, and species compositions, and more, the same quota basket applied to two different fisheries might result in very different outcomes. For successful quota basket management, a fisheries manager must understand how a proposed quota basket will influence the target fishery.

Tradeoffs for the basket allocation are well understood.

Quota baskets are intended as a relatively simple management scheme that can improve the outcomes of many fisheries. Quota baskets are not intended to achieve perfect fisheries management, whatever that may be. As a result, every quota basket has tradeoffs. In our modeling, we see that a fishery with two baskets cannot achieve the profits that a 3, 4, or 5 basket scheme might (Figure 2). Furthermore, a two basket scheme can result in stocks at dangerously low levels (Figure 3). However, a two basket scheme likely requires fewer monitoring and enforcement costs than a 4 or 5 basket scheme, and two baskets can improve profits for the fishery compared to a global quota.

When implementing a quota basket in the real world, understanding these tradeoffs ensures that the sacrifices made under each scheme are acceptable for a given fishery. All fisheries management consists of tradeoffs, so this precedent is well understood, but quota baskets do carry significant risk of stock collapse and other detrimental effects. This risk is so severe that others have discarded quota baskets as a viable strategy, though we show that carefully implemented baskets can still improve fisheries outcomes (Bonzon et al., 2013).

A stark example of acceptable tradeoffs is China's management of fisheries: China has determined that maximizing food production goals and reducing monitoring and enforcement costs is worth severe depletion of some target species (Szuwalski et al., 2017; Costello, 2017). A second example is our Bering Sea harvest cap, where low harvest limits sacrifice revenue and yield in favor of sustainable fisheries (DiCosimo et al., 2010; Melnychuk et al., 2013). We hypothesize that simpler quota baskets will suffer more from trade offs, though additional work is needed to support this claim. Regardless, understanding the tradeoffs with any quota basket scheme is key for any manager.

Quota baskets are easy to understand and enforce.

A major benefit of quota baskets is that they are relatively simple management schemes that manage to improve fishery outcomes. We show that two quota baskets can considerably improve fisheries outcomes compared to one global quota (Figure 2). However, it is entirely possible to group species based on a trait unknown or unclear to the people participating in the fishery. A good example is trophic level: while a fishery biologist has a clear understanding of trophic dynamics, the concept is not commonly understood, very difficult to measure, and hard to enforce. Complicated, vague, or abstract quota baskets will likely require significant resource allocation for successful implementation, as education, monitoring, and enforcement becomes more difficult. While complicated schemes might appear to drastically improve fisheries outcomes on paper, complicated and expensive schemes run contrary to the core idea of quota baskets: better management in a simple way. After all, highly effective, resource management schemes are well studied and often employed in fisheries, like ecosystem based management, and a good choice for managers with the requisite capitol (Pikitch et al., 2004). Quota baskets are intended to improve fisheries that cannot allocate the resources necessary towards implementing complicated schemes, and as a result, quota baskets must be easy to understand, monitor, and enforce.

One basket grouping may not be enough to meet the goal.

While grouping a fishery based on one characteristic is a simple way to improve some fishery outcomes, a single grouping parameter may lead to unwanted consequences, like species extinctions. Our model prevents stock extinction because the allowable harvest for each species is calculated as a percentage of stock biomass. However, real world harvest limits cannot necessarily prevent fishing stocks below critical levels, and global fisheries often suffer from stock depletion (Worm et al., 2009). While our modeling results focus on imposing one quota basket grouping on a fishery, it is possible that multiple quotas are necessary to protect particularly vulnerable or important stocks. In the Pacific Groundfish fishery, species are currently categorized and managed by many more harvest quotas than initially implemented (PFMC, 2015). A global quota for the fishery could not prevent overfishing of certain weak stocks, and so additional management measures were needed.

Additional management actions are not limited to harvest quotas, and other strategies, such as catch shares or no-take MPA's, can be used in conjunction with a quota basket scheme. Difficult enforcement might be remedied through individual tradable quotas or individual vessel quotas, depending on the fishery. Other scenarios might warrant an application of some tools of portfolio theory to achieve fishery diversification, like a variance-covariance array across species to stabilize fishery earnings by minimizing risk from seasonality, natural hazards, and economic shocks (Sanchiriro et al., 2006.)

Limitations and other concerns

Our model modifies a surplus production model to account for quota basket groupings and the resulting fishery dynamics. However, we make crucial assumptions that may not reflect real-world fishing in our analysis. First, we assume zero bycatch discards, assuming that all species are sold at the market for their full price. While some multispecies fisheries might sell fish indiscriminately, in reality, fishers target fish they can sell and are likely to discard fish that aren't those (Batsleer et al., 2015). The model hints at some potential effects of incorporating discarding. In the first place, some results imply the fishermen minimize the allocation of effort in the low-trait species to maximize the extraction of the profitable species. This reflection is reinforced by the low incidental catchability value (off-diagonal) that does not seem to deter from zero specialized effort assignment on low-trait baskets. In actual fisheries, the discard amount will increase with the value of incidental catchability and profitability difference among species. These findings are concerning because it verifies the unequal depletion risk (Bonzon et al., 2013) and reveals that once the high-profit stock declines, the two low-trait stocks also experience a notable reduction. Besides, our quota cap criterion augments this situation because it also maximizes profitability. A potential solution is constructing a quota basket cap that balances profit and conservation goals, binding the harvest of different species within the basket.

Additionally, we use a simple cost structure in many of our analyses. Our model's central assumption is that fishers face no switching costs between technologies, allowing for near-optimal effort allocation that does not reflect real-world constraints (Selgrath et al., 2018, Noack & Costello, 2019; Cashion, 2020). Incorporating switching costs could cause time lags, shift optimal arrangements, and reduce our model's profit outcomes. Besides, fishers have different starting fishing gear that might be difficult to replace during the first years of quota basket implementation. In this context, it is reasonable to think that some technologies have substantial exit barriers due to constraints like financial resources, capital lifespan, and expected returns. In this context, we theorize that a quota basket might improve the planning of effort allocation, but those adjustments would be gradual over time. Another source of switching costs is the transformation capital associated with factories. A technological shift can provoke unbalanced supply to local factories or displacement of fishing overcapacity. While the latter is good news for conservation goals, it will cause social conflict.

Our second cost limitation is the omission of monitoring costs. We theorize that quota baskets imply fewer monitoring costs because the fisheries are regulated as a group. While some quota baskets (territory, time, size) can be cheap, other approaches are resource-intensive by definition (trophic level, ecosystem function, risk). Depending on the number of baskets, the manager might be motivated to instead channel its capacity into gradually implementing a few single-species schemes. Furthermore, it can be riskier to introduce quota baskets for 100 fisheries than 10 species simultaneously if the authority lacks basket design experience. Still, quota basket and single-species management are complementary schemes that can benefit from each other.

Finally, while quota baskets can improve aspects of fisheries management, specific problems persist. For example, with any quota scheme, discarding and high grading is an issue. A quota basket scheme may exacerbate these tendencies, as all fish in a basket count towards a quota. Bycatch that is far less valuable than a target species still counts towards the quota, which incentivizes discarding these undesirable fish. There may be additional fishery problems that quota baskets make worse, some specific to individual fisheries. We encourage thinking critically about any quota basket scheme and how it may influence the fishery's participants and behavior.

Conclusions

Our report is the first formalized, analytical model of a quota basket approach to multi-species fishery management. Quota baskets share some similarity to approaches such as portfolio management, but are notably different (Sanchirico, 2003). Our report uses a simple profit maximization model to examine the fundamentals of quota baskets, provide a foundation from which to compare to other management approaches, and to further develop quota basket theory.

Quota basket management has historically been ignored because of high risks associated with grouped quotas, but we showed that quota baskets can improve fisheries management without causing significant harm (Bonzon et al., 2013). In fact, quota baskets can increase fishery profits compared to global management even in a simple two-basket scheme. While our theoretical approach does not capture the full nuance of real world fisheries, our results suggest that quota baskets are a concept worth exploring for many “middle ground” fisheries. Furthermore, we suggest a few simple ground rules for designing and implementing quota baskets in the real world that will help a manager avoid poor outcomes. Our results also suggest that fishery outcomes are highly dependent on basket construction, fishery characteristics, and harvest limits within our model. For a manager to actually consider a quota basket scheme, significant fishery specific work must take place to understand how different baskets will affect the fishery outcomes. This report provides the only guidelines for considering quota basket management, and is a crucial step towards considering quota basket management as a viable, real world management scheme.

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Appendix

Appendix 1: Rethinking fisheries

Overview:

The objective of this research is to reframe current fisheries management under our quota basket approach. This approach focuses on establishing grouping criteria by characteristics (or traits) that can be economical, biological, or social. However, the stakeholder's interpretation of the bundling trait can modify the basket design and its purpose. For example, according to a territory, grouping species might imply critical habitats, local markets, community locations, or jurisdictional regulation. Each one, or a combination of them, can be considered a territory-based basket, but they may prioritize different goals (Table A). Understanding the internal (values, morals, biases) and external factors (economy, society, peer pressure) is critical to influence a shift in behavior (Azjen, 1991). The stakeholder's interaction with the species is relevant because there might be additional value sources beyond price (food security, culture, tradition). Having regard to these considerations, this section will review the benefits and drawbacks of potential grouping criteria.

Table A: Goals, challenges, and target variables by stakeholder in the fishing sector

Stakeholder	**Goal**	**Challenges**	**Target variables**
Authorities (consider the participation of multiple stakeholders)	- Economic and development growth -Minimize political and social costs -Reference value of the goal	-Limited budget -Credibility loss -Policy delay -Misreporting -Preference for status quo	-Political costs and governance -Management and enforcement costs -Adjustment costs -Tradeoff costs (biomass, jobs, taxes, food security)
Scientists (Anticipate opposition, reduce uncertainty, provide insight about sustainable biomass)	-Conservation and - Minimization of ecosystem harm - Provide insight about sustainable biomass levels and Reduce uncertainty -Anticipate opposition	-Limited budget -Limited information -Limited political power -Human error -Uncertainty -Lack of transparency	-Biological and physical variables -Trophic level -Monitoring costs
Fishermen (seeks income or business consolidation,, recognitions, trust, keep traditions, belong to a community)	-Maximize profits/income today - Industry consolidation - Risk reduction - Income diversification - Employment - Food security - Development	-Overcapacity -Illegal, unreported, and unmanaged fisheries -High grading, bycatch, and discarding -Inadequate fishing gears -Policy anticipation	-Profits (price and costs) -Social norms -Monitoring costs -Financial tools -Investment -Taxes -Property rights

Based on Godfrey & Fujita (2016) and modified with information from Ono et al. (2017), Silva & Lopes (2015), Van Vugt, M. (2002) and Van Vugt et al. (2000)

Quota basket approaches

Quota basket theory emerged from a search for alternative strategies that may improve Chinese fisheries' catch diversity and ecosystem function while meeting food security and economic goals. According to the current trophic balance imposed by years of top-down fishing pressure, the thinking was that managing Chinese fisheries might maintain high catches while improving ecological and economic outcomes.

A **quota basket based on an individual fish's trophic level** is tempting because the resulting management strategy encompasses broad-scale ecosystem dynamics, similar to how an ecosystem-based management scheme might. This is increasingly relevant in global fisheries, as decades of high fishing pressure have caused fishery catches to decline, on average, in a trophic level (Pauly et al., 1998). Furthermore, overfishing in the context of global change threatens to cause regime shifts in many of the world's fisheries (Maureaud et al., 2017). Trophic baskets that limit the overfishing of high trophic level stocks might restore balance to the fishery ecosystem and potentially halt an impending regime shift.

Organizing a fishery into trophic baskets can also provide a powerful tool to maximize a fishery's yields. Whether the results are intentional or unintentional, this approach maintained high fishery yields in China. This increased yields result from the removal of apex predators from their marine food web, and similar ecosystem responses have been observed in other fisheries worldwide (Frank et al., 2005; Myers et al., 2007; McClanahan et al., 2008; Szuwalski et al., 2017). Real-world fisheries have seen fishing-induced yield increases mainly as a byproduct of intense fishing pressure on high trophic level species. As a result, a growing theoretical literature suggests that intentional manipulation of food web structure may be the best way to increase food provision from many fisheries (Anderson et al., 2015; Matsuda et al., 2006).

A trophic level quota basket allows a manager to reap the food provision benefits of ecosystem manipulation with a single strategic harvest limit for high trophic level species. Additionally, low quotas on high trophic level species, which are often high-value target species, may encourage catch diversification, a proven mechanism for increasing a fishery's resilience and revenues (Yletyinen et al., 2018, Robinson et al., 2020). In this manner, a trophic level quota basket can improve profits, harvest, and economic resilience.

Of course, a trophic level basket has limitations. Trophic levels are tough to measure, and a harvest limit for a trophic basket is at best expensive and at worst impossible to enforce (Carscallen et al., 2012). Further complicating things, a single species can fluctuate between several trophic levels through its life, making the trophic level of an individual fish challenging to quantify (Laiz-Carrión et al., 2015). An additional disadvantage of a trophic basket is that trophic levels are a relatively abstract and niche concept, increasing the likelihood that fishers or regulators misunderstand or misenforce the quota.

A proxy for a trophic level that is easier to understand, monitor, and enforce is an individual fish's size. A **size-structured quota basket** might leverage this into a successful management scheme. Size is not a perfect indicator of trophic status, especially between species or for herbivorous fish, but it can provide straightforward baskets related to trophic status (Jennings et al., 2002; Keppeller et al., 2020). Furthermore, a size-based basket has additional advantages as well. In most markets, we tend to find that consumers prefer species with larger body sizes and larger specimens within a species (Tsikliras & Polymeros, 2014; Sjöberg, 2015). Size limits are already commonly imposed on fisheries, generally as hard constraints (i.e. a minimum size requirement) rather than size-based quotas (i.e. a limit on 5-10 inch fish) (Reynolds et al., 2001). Size-based quotas intend to let individual fish age to maturity before harvest (Beverton, 1992).

Additionally, in specific fisheries, size baskets may reduce pressure on the largest, oldest individuals of some populations, often the most fecund fish (Hixon et al., 2014). This can occur if the largest, most valuable individuals are in a basket where fishing effort is better spent targeting other species. Finally, some fishing gear restrictions, namely minimum mesh sizes for nets, implicitly organize fish into size baskets: those below and those above the minimum mesh size. Thus, a **gear-structure quota basket** is another facet of a size-basket, and it is employed when the focus is the fishermen's behavior and installed fishing capacity. The establishment gear baskets can improve landing predictability, gradual overcapacity and intensification reduction, and gear shifting (Chuenpagdee et al., 2003; Selgrath et al., 2018). In this manner size and gear baskets can contribute by aligning conservation and social objectives.

Size and gear baskets have shortcomings as well. Because juveniles and adults from different species can be the same size, there is no limit to catching fish well below maturity and disrupting the food web balance. In an extreme case, a fishery with one extremely-valuable fish relative to the other fish could see fishers target that fish at every size, overfishing the valuable fish. The favoritism for a high-value species motivates practices like high-grading, where the least valuable fish are discarded to have increased storage availability per trip (Sanchirico et al. 2006). Furthermore, poorly planned size and gear baskets might shift targeting to specific life stages of certain fish, causing demographic instability in these populations. Another challenge comprises the authority's capacity to enforce size limit, legal gear, and the fishermen's gear predilection. The fishermen might be opposed to size and gear restrictions because (i) their capital investment might be too high (overcapacity), (ii) significant exit barriers exist, (iii) the current technology is good at harvesting multiple commercial species, and (iv.) shifting technologies endangers society's household lifestyle. In this setting, the success depends on the budget availability, monitoring capabilities, and the authority's ability to conduct a program to train and compensate the agents affected by this technological transition.

Territory structured baskets are the most straightforward approach that involves species, stakeholders, and management goals. The definition of the jurisdiction boundaries (critical habitats, local communities, markets, etc.) depends on the stakeholder's prioritization. Territory baskets contribute to maintaining ecosystem functions, conservation (marine reserves), and food-security (Territorial Use Rights for Fisheries) goals. The **ecosystem functional groups** can be managed to preserve full ecosystem function without requiring single species quotas. While biodiversity in many ecosystems is high, the functional diversity of an ecosystem, or how many unique roles a species may occupy, is far lower (Tilman, 2001). Fishing pressure has caused functional group shifts in many of the world's fisheries, and protecting functional diversity leads to resilient, sustainable fisheries (Mouillot et al., 2013; Villeger et al., 2017; McWilliam et al., 2018; Trindade-Santos et al., 2020).

Furthermore, this strategy can allow selective targeting of certain fish while simultaneously ensuring the entire ecosystem balance is not disrupted. A functional group strategy will enable fishers to continue to target high-value species while preventing the whole functional group's collapse. While such a strategy may contrast with conservation goals, a functional group strategy can improve ecological outcomes while maintaining fishing similar to the status quo. This grouping is particularly applicable to fisheries in places like China, where food security and fishers' livelihood goals are prioritized (Cao et al., 2017). On the other hand, the protection of critical habitats by **marine reserves** enhance diversity (Halpern, 2003), population (Lester et al., 2009), and resilience to climatic impacts (Micheli et al., 2012), enabling the spillover of the species to adjacent areas (Halpern et al., 2009). Alternatively, the **TURFs** provide similar outcomes to reserves by eliminating the Olympic race to fish (Cancino et al., 2007). There is evidence that this territorial organization can work synergistically (Costello & Kaffine, 2010): the spillover from the marine reserve reinforces the TURF's resilience. In other words, a conservation basket (no-take zone) supports a food security basket (TURF). Consequently, territory baskets contribute to recognizing ecosystem services, conservation hotspots, empowerment of local communities and lifestyles, and implementation of property rights easy to understand.

Territory structured quota-baskets are easy to explain but difficult to implement. Its allocation is complex because high-mobility species and ecosystem functions might range in a vast extension overlapping multiple jurisdictions, interests, and conflicting goals. Consequently, a territory might be expensive in compiling scientific evidence, coordinating with different government levels, and engaging various involved agents. Disturbances like El Nino events exacerbate the shifting in ecosystem processes and fish migration and require additional planning and negotiation resources. In establishing synergies between baskets, Afterbach et al. (2014) recommend that a TURF-reserve favor fast-growth species to set adequate income expectations in local communities might improve income and spread support for these schemes. Lastly, strong institutions in all involved levels are required to organize, monitor successfully, and enforce these schemes, especially when many stakeholders participate. In this sense, the information about the community structure (leadership, self-regulation methods, and history) is crucial when organizing multiple interests (Van Vugt et al., 2000).

A poorly explored version of the territory basket is a **quota basket based on market categories.** Often, seafood items are grouped and sold according to their markets that differ from their management or ecological types. For example, in Florida, snapper species are scattered throughout different management complexes (NOAA, 2020a) but sold according to their name. In fact, within a management complex, prices can vary markedly. For example, the average price of snappers in the deepwater complex was $3.61 per pound in 2019, but Blackfins only fetched $2.98 per pound while Queens could bring $4.01 lb. (NOAA, 2020b). Bentousi (2020) found that under this type of varying prices, price increases result in increased fishing effort, while Elfoutayeni (2020) found that incorporating this scheme into a competition model for space and food resulted in an optimal harvest strategy that differed markedly from one without varying price.

A **time-structured** quota basket incorporates the species' variability due to biological, climatic, and consumer preference factors (e.g., increased fish consumption during the Holy Week). The establishment of seasons trades a "myopic optimization" within the year for a formalized harvest plan. Shah & Yeolekar (2016) found that if incentives are adjusted to spread out the harvest of a high-value species over a season within multispecies fisheries, lower-value species could end up being harvested earlier. They found catch can be unresponsive to biological aggregation (i.e., seasonality, spawning, etc.) when fishers balance incentives in multispecies settings. Thus, when targeting more than one species, fishers are weighing the opportunity costs associated with each species, which differ due to the underlying differences in characteristics between the species. The summer moratorium in China is an excellent example of a time-structured basket. A potential advantage of a time quota basket might save monitoring, enforcement, and social costs if many species share similar behavior over time (reproduction season, intrinsic growth speed, migration patterns, juvenile catch rate, and disturbance sensitivity). Consequently, combining slow-growth and quick-growth species in a basket because each species' depletion and recovery will not coincide. Besides, the extraction of a rapid-growth species delayed by sharing the basket with a slow-growth species will cause social pressure and conflict. Lastly, a time quota without complementary actions (like population monitoring, individual quotas, and effective closures) will fail because disturbances (e.g., El Nino) and the Olympic race might alter the season's predictability. A time basket contributes to adequate planning, income and employment stability and overcapacity reduction.

Previous basket groupings intend to preserve broad-scale ecosystem, economic, social arrangements, but it is possible to bundle on specific species characteristics: **current status, growth rates, and life histories.**

A straightforward application of quota baskets is to group fish into **two categories: threatened species and stable stocks**. A manager with conservation goals might set a low quota for endangered species and allow more fishing for stable stocks. Additionally, for severely threatened stocks, a quota of zero can enable the population to recover. Similar "reactive quotas" are already commonplace, where the allowable catch of an individual species is related to their population status (Hilborn et al., 2020). However, current reactive quotas are based on single-species stock assessments, which are resource-intensive. The quota basket approach encourages grouping species into categories, like endangered, threatened, and stable, then managing each group with an individual quota. This circumvents the need for extensive stock assessments, as an estimate of status is adequate. Status-based quota baskets are most potent when stacked with other baskets as an additional way to protect the most vulnerable species. Another major limitation is individual species can suffer when grouped in a basket. Adding a basket based on status might allow vulnerable stocks to recover in a management scheme.

While reactive quota baskets, like a status basket, might prevent the collapse of exploited species, a proactive grouping can group species based on their overexploitation risk. We can also frame this as grouping by **species exploitability**. A simple proxy for this might be a species growth rate, r, where fast-growing species can respond to higher fishing pressure than slow-growing species (Pinsky & Byler, 2015). The link between growth rates and exploitation risk was recently observed for tunas, where slow-growing tunas are more likely to be overexploited than their fast-growing counterparts (Juan-Jordá et al., 2015). Several real-world examples exist of slow-growing species suffering from high fishing pressure, including the near extinction of a skate (Brander, 1981) and the collapse of West Coast rockfish species (Brodziak, 2002).

Actual species susceptibility is based on a combination of life-history parameters and the real likelihood a fish is caught. Basket groupings based on species susceptibility allow a manager to fish resilient stocks at a high level while limiting fishing on vulnerable stocks. Several frameworks exist that categorize species based on their **susceptibility**. Fish species are increasingly studied based on their life history grouping. Several frameworks exist for species groupings, and these frameworks incorporate life-history parameters such as growth rates, a number of offspring, age at maturity (Adams, 1980; Purvis et al., 2000; Reynolds et al., 2005; Hutchings et al., 2012; Kindsvater et al., 2016). A more comprehensive framework is the susceptibility scoring system applied to West Coast Groundfish, which combines biological susceptibility with fishing stressors to rank species based on their risk of overfishing (PFMC, 2010). A quota basket scheme that encourages harvesting species based on their tolerance to fishing can be created from any of these frameworks and can maintain high fishery yields while protecting vulnerable species.

Prices are the ultimate factor that directly influences fishermen's behavior. Being profit-driven, fisheries follow the law of supply: when supply is high, prices tend to drop (Baker, n.d.). The law of one price also holds, especially in well-integrated markets: when demand is high, similar products rapidly flow across geopolitical boundaries to satisfy the demand (Asche et al., 2012). In a competitive market, prices reveal information about species scarcity (health status, growth rate, season), consumer preferences (quality, origin, nutrition value, flavor), substitutes, and speculation. In the presence of market failures like imperfect information, public goods and monopoly, it is natural to think about **price-based quota** to shift the fishery towards an economic optimum that ultimately results in high profits and stable stocks. Bioeconomics theories (FAO, 1998) indicate that the fishery's economic optimum is at a lower harvest level than the biological optimum. And yet, actual pricing mechanisms are rarely explicitly considered in modeling (Nielsen et al., 2018) or management frameworks, leading to potentially suboptimal harvest strategy recommendations. The main reasons for using exogenous prices are their multiple determinant factors, variability, and many stakeholders' not influencing them in international markets (price takers). Dissecting all these components requires time and resources that might distract us from other fisheries' traits. Another disadvantage is prices are not enough to identify fishermen's behavior: we also require knowledge about how costs determine fish profitability. We need to be careful about setting the incentives because a high-price species may be attractive, but it does not mean that the costs are not prohibitive for the majority of agents. On the other hand, authorities have restricted access to cost data, and, many times, price is the only available information. In conclusion, prices are not the only factor for quota basket design, but they cannot be omitted.

Risk is another potential criterion for quota basket building because stakeholders monitor the hazards that endanger their status quo. A risk-structure quota basket seeks the same goals of portfolio management of fisheries: maximize returns and diminish the variability in the productivity and population in multiple stocks (Sanchirico & Smith, 2003; Perusso, 2005). **Risk-structured baskets** can consider the species variance and covariance in critical variables (profits and biomass) to set a strategy that maximizes profits while minimizing variability over time. A criterion can be grouping the species with negative covariance to avoid the abundance shifts across fishing seasons. Despite the attractiveness of multiple portfolios, it requires routinely collected information to justify a robust evaluation of the tradeoffs between return and risks. Information of quality and a clear understanding of the stock dynamics are essential for the right policy prescription (Sanchirico, Smith, & Lipton, 2008). Lastly, this approach is challenging to communicate to the involved stakeholders because it involves dynamic prices, ecological variables, and variability.

Appendix 2: Original Case Studies

Overview:

Quota baskets is a reframing of fisheries management, rather than a truly novel method. As a result, certain fisheries have implemented quota basket schemes, but called them as other names. In this section, we pick two examples of similar fisheries, one managed with a quota basket and one without, that resulted in very different outcomes. The first is the Pacific Groundfish fishery, a large multispecies fishery where many stocks collapsed from poorly set single species harvest limits. As a counterexample, we then examine the resounding success of the Bering Sea and Aleutian Islands groundfish fishery, where a two-million ton quota basket has prevented overfishing and stock decline for the last thirty years.

Pacific Groundfish

How is the Pacific Groundfish fishery a quota basket?

The Pacific Groundfish Fishery currently includes 90 species across four groups. There are four elasmobranchs, six roundfish, 60+ rockfish, and twelve flatfish included in this fishery, and the fishery extends along the entire Pacfic coast of the United States EEZ (PFMC, 2016).

A mixed species fishery with high spatial variability, significant species level and genus level variation, significant variation in the amount a species has been studied, and heterogeneity in fishing intensity and character beckons a complicated management scheme: indeed, current management practices for Pacific Groundfish include efforts such as single-species stock assessments to set individual species quotas; bycatch regulations; catch-shares, and gear restrictions (PFMC, 2020; Kauer et al., 2018).

However, the Pacific Groundfish fishery initially relied on a very simple management scheme, where a single MSY was set based on assumptions about groundfish species' life history characteristics and then applied to the whole fishery (PMFC, 2016). This single harvest quota applied to an entire multispecies fishery is a quota basket.

Species involved in the Pacific Groundfish fishery

The Pacific Groundfish fishery contains species with a wide variety of life histories. Elasmobranchs, for example, are slow growing, long-lived species, whereas most flatfish grow relatively quickly (NMFS, 1990). Even within the same genus, species can exhibit vastly different life-histories. For example, *Sebastes* species range from extremely long-lived and slow growing species like *S. rosenblatti*, with a maximum age of ~50 years, to short-lived, fast growing species like *S. hopkinsi* (Love et al., 1990). This wide variation in life histories is an important characteristic of the Pacific Groundfish fishery.

Species also exhibit significant habitat variability, and are heterogenous in which habitats they occupy and the depth at which they are caught (PFMC, 2010; Miller et al., 2014; McCain et al., 2019).

Additionally, fish command very different prices and have significant variation in market demand (NMFS, 2020). Sablefish and Pacific Whiting have historically generated over 50% of the total groundfish revenue since 2003, and likely before then as well (NMFS, 2020). Non-whiting revenues are distributed evenly across different gear types, with non-whiting trawling generating most of the non-whiting fishery revenue. Non-trawl technology generated a small portion of revenue relative to trawling in the non-whiting fishery (NMFS, 2020).

The Pacific Groundfish approach

The challenge in managing a diverse fishery like the Pacific Groundfish fishery is balancing the wide variety of life histories, species exploitabilities, markets, and gear types so that the fishery generates as much revenue as possible while protecting the most susceptible species to overfishing. Robert Francis, in a report modeling stock response to multispecies fishing in the *Sebastes* species complex in Southern California, concluded that the more diverse a species management target is, the more conservative the allowable catch must be (Francis, 1986). The challenge here is setting a quota conservative enough to protect the most vulnerable species, but large enough to maximize revenue from the fishery. Francis showed that a single harvest limit for a multispecies fishery inevitably leads to lost revenue compared to tailored species quotas, and that overfishing certain species is still possible even with a quota that results in lost revenue (Francis, 1986).

Initial groundfish management attempted to pick one harvest rate for the whole fishery that got as close to maximum yield as possible while keeping the risk of overexploitation low. Based on the best science at the time, managers picked a harvest level of $F_{mmy} = 35\%$ for each species, or fishing stock levels down to 35% of their stock levels before exploitment (NMFS, 2020; Clark, 1991). This level was specifically selected as a conservative harvest rate expected to minimize the risk of overharvesting even if managers knew almost nothing about the stock life histories involved.

Results of the Pacific Groundfish Quota Basket

How did one harvest rate applied to each species perform? Poorly, in 1998, a survey of several important commercial groundfish species showed significant overfishing and continued population declines with no foreseeable trajectory to reach equilibrium harvest with current mortality levels (Ralston, 1998). In other words, the fixed harvest rate chosen for each species was still too much fishing for some species to handle.

In addition to significant biomass declines in “weak stocks”, this approach also significantly impacted fishery revenues. Pacific Groundfish lost revenue from overexploitation and collapse of the fishery. Revenues in 2000 were half of what they were in 1982 (Warlick et al., 2018). This was the culmination of two separate phenomena: declining stocks leading to diminishing harvest, a result of overfishing and poor environmental conditions; and extremely low harvest limits as an attempt to reduce fishing pressure on stocks near collapse.

Charting the decline of revenues in the Pacific Groundfish fishery reveals a few truths about fisheries management important for quota basket theory. The first is that fishers will fish beyond maximum sustainable yield when left to their own devices. This is, of course, a well known consequence of open access fisheries, (Bjorndal & Conrad, 1987) but potentially less clear under multiple quotas, like was initially implemented in the Pacific Rockfish Fishery. The second is that maximizing revenues in the near term can have significant consequences in the long term, and that more stringent management implemented earlier that prevents fisheries collapse may actually increase total revenues from the fishery over time.

Consequences of a diverse fishery in the Pacific Groundfish Quota Basket

The initial constant mortality management policy for Pacific Groundfish failed for one major reason in particular: groundfish were far less productive than the "average" demersal fish managers used as a baseline for harvest limits (Myers et al., 1999). Furthermore, some species within the groundfish group were particularly unproductive, leading to significant rates of overfishing in select species (NMFS, 2020).

In 2011, Cope et al. characterized life-history traits and other characteristics into susceptibility categories, then ranked the susceptibility of overfishing for each species in the Pacific Groundfish fishery based on their attributes (Cope et al., 2011). They quantify two different metrics for stock vulnerability: productivity, which is mainly based on fishes life histories, and susceptibility, which is based on how a stock interacts with the fishery.

Productivity is based on fish life histories, and this analysis reinforces the importance in understanding a fishery's life histories when making management decisions. Rockfish are some of the least productive species in the ocean, with generally slow growth rates, long lifespans, and old age at maturity. Low productivity alone is enough for rockfish to be considered at moderate-high risk of overfishing, whereas flatfish are relatively productive and receive a low score (Cope et al., 2011). This analysis can guide setting a quotabasket for a wide variety of species, where the least productive species are, from the start, the most vulnerable to overfishing. In the Pacific Groundfish fishery, species that suffered the most had generally low productivities (MNFS, 2020).

The second vulnerability metric, susceptibility, explores how a species interacts with the dynamics of fishing within a fishery. This is generally split between how a species interacts spatially, and how likely a fish is to be caught using the targeted gear (Cope et al., 2011). For groundfish, their susceptibility is related to their spatial relationship with the fishery, plus the catchability of each fish within the fishery. Being a trawl fishery, the most susceptible species are those with large area and depth overlap with fishing pressure, and also those exhibiting high catchabilities in the trawl gear (PFMC, 2010; Cope et al., 2011).

What can we take away from this analysis? Of the two ways a species might be vulnerable to overfishing, productivity is based on a species' biology, and susceptibility is based on the characteristics of a fishery. Of the two, susceptibility is likely to evolve over time as fishing technology, pressure, and regulations change, while vulnerability is a more static measure. Understanding how a quota basket will affect a fishery requires understanding both productivity and susceptibility.

Lessons learned from the Pacific Groundfish fishery

The Pacific Groundfish fishery decline has several key takeaways for quota basket theory. Generally, a poorly studied multispecies fishery is a risky candidate for grouped multispecies management: the risk of one or several stocks being overfished is too high. Similarly, quota baskets may not work for fisheries with diverse life histories yet similar catchabilities, as evidenced by the collapse in certain “weak stocks" in the fishery. Third, the best management requires good stock assessments and monitoring. Fourth, baskets will always sacrifice some revenue compared to optimal single species management, but poorly set quota baskets can cause significant declines in long-term revenue and significantly harm fishers’ livelihoods.

Bering Sea Groundfish

How is the Bering Sea groundfish fishery a quota basket?

Since 2005, the Bering Sea groundfish fishery has operated under a 2 million ton annual cap, where the total fishery harvest each year must not exceed 2 million tons. This is a quintessential quota basket, where all groundfish are grouped together in a single basket with a single harvest limit.

A stark contrast to the complex, reactive management history of the Pacific Groundfish, the Bering Sea groundfish fishery management history mainly revolves around bycatch controls (Witherwell & Pautzke, 1997). This is largely because no single species in the fishery has ever neared collapse. So, while Pacific Groundfish has gone from a failed quota basket scheme to more intricate management, the Bering Sea Groundfish has applied a quota basket as an additional management measure on an already stable fishery.

However, the recent global cap is not the only quota basket approach the fishery has taken. Initially, the fishery set a single species Total Allowable Catch for just a few individual target species, while the remaining species were grouped into species complexes. For example, between 1980 and 1988, there were harvest limits set for three species complexes: flounders, rockfishes, and “other species” (NPFMS, 2005). While these groups have been broken down into finer management arrangements since then, the groupings did not lead to negative outcomes in the fishery.

Species involved in the Bering Sea groundfish fishery

The species involved in the Bering Sea groundfish fishery are similar to those in the Pacific Groundfish fishery (NMFS, 2015). After all, the fisheries bookend the same California Current ecosystem. Species include pollack, cod, several flatfishes, sablefish, mackerel, numerous rockfishes, squid, a few sharks and rays, and squid (NPFMC, 2015). The species include a broad range of life histories, with variation in species similar to the variation found in the Pacific Groundfish fishery. A notable exception is that the “other species” category includes squids and octopus, which are not fish and not managed in the Pacific fishery. However, these species are common target or bycatch species of the fishery.

Results of the Bering Sea two million ton cap

The Bering Sea Groundfish fishery is managed by a global quota (2 million tons) and additional individual harvest limits, for either single species or complexes. The single species harvest limits are set at $F_{40\%}$ for many stocks and complexes, where the stock levels must not fall below 40% of their unfished levels (NPFMC, 2015). This is similar to the initial harvest limits set for the Pacific Groundfish fishery. So why, then, has the Bering Sea groundfish fishery avoided any signs of overfishing and collapsed stocks?

The answer lies in the global quota. A two million ton quota is a relatively conservative quota for the fishery, and historical fishing has occasionally exceeded 2 million tons (Witherell et al., 2000; PFMC, 2015). In fact, the two million ton cap is well below the sum harvest if each species was fished at 80% of maximum sustainable yield (Witherell et al., 2000; DiCosmo et al., 2010; Melnychuk et al., 2013). Bering Sea groundfish occupy a wide range of market demand, where pollack fetch a much higher price and have a much larger market than other species (PFMC, 2015). As a result, the majority of the fishing effort in the Bering Sea is put towards pollack, and pollack catches fill over half of the quota (PFMC, 2015). The remaining quota is split between all of the other species in the fishery. The relatively limited remaining quota keeps fishing pressure on all the other species low, maintaining a sustainable fishery.

A side effect of the very successful global cap is that management can focus on fine scale improvements rather than outright stock recovery. For example, harvest limits were at first generally applied to species complexes in the fishery. Over time, harvest limits were improved, and many target species in the fishery have had full stock assessments completed (PFMC, 2015). A well implemented quota basket allowed more costly management initiatives to be implemented over time, delaying the associated costs. Additionally, Bering Sea fishery management now focuses on proactive measures like bycatch reduction, anticipating future problems before they manifest in stock collapse (Witherell et al., 1997; Alderstein & Trumble, 1998; Branch & Hilborn, 2008).

Key takeaways from the Bering Sea case

The Bering Sea groundfish global cap shows that quota baskets, even for a group of species with diverse life histories, can be very successful. There are a few key dynamics that led to the Bering Sea success. The first was a conservative harvest limit. Second was an understanding of the dynamics of the fishery. This basket mainly succeeded because most of the fishing pressure went to pollack, a high value species. Had pollack been slower growing, or had rockfish been the more expensive fish, some species might have collapsed. Understanding which fish are managed in a basket is key. The third key takeaway is that interim management measures, like quota baskets, introduce sustainable fisheries management that can always be improved upon later. Due to the success of the original management plan, the Bering Sea groundfish fishery has been able to focus on improving and expanding management within the fishery in the years since. Similar fisheries that want or need some regulation might see quota baskets as a stepping stone to more complicated management in the future.