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ARTICLE

Does more fish mean more money? Evaluating alternative escapement goals in the Bristol Bay salmon fishery[1]

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Abstract: We develop an economically sophisticated management strategy evaluation for four sockeye salmon (*Onchorhynchus nerka*) fishing districts in Bristol Bay, Alaska, to evaluate whether proposed increases in escapement goals — the number of fish allowed up each river to spawn — could improve fishery outcomes for the industry and the region. Higher escapements increase average runs toward biological maximum sustainable yield, but this is driven by infrequent years of very abundant runs. Our economic model shows processors do not add capacity in response to infrequent abundant runs. Therefore, interannual variance in district-specific catch increases because years with little or no fishing become more frequent to meet higher escapement in low-run years, but industry cannot capture greater value in the high-run years. In abundant runs, processors shift available labor to focus on high-volume, lower-margin products; in very abundant years, insufficient processing capacity allows additional fish to escape. Mobile driftnet vessels that can move to rivers experiencing high runs each year benefit, but district specialists in the small boat and set-net fleets are more vulnerable to years with little or no catch.

Résumé : Nous développons une évaluation de stratégies de gestion économiquement complexes pour quatre districts de pêche au saumon rouge (*Onchorhynchus nerka*) dans la baie de Bristol (Alaska) pour déterminer si des augmentations proposées des objectifs d'échappement, soit le nombre de poissons qui peuvent remonter chaque cours d'eau pour frayer, pourraient améliorer les résultats des pêches pour l'industrie et la région. Un plus grand échappement accroît les migrations moyennes qui contribuent au rendement équilibré maximal biologique, mais cela est principalement le fait d'années peu fréquentes de migrations très abondantes. Notre modèle économique montre que les transformateurs ne rehaussent pas leurs capacités en réponse à des migrations abondantes peu fréquentes. La variance interannuelle des prises par district augmente donc parce que les années où il y a peu ou pas de pêche deviennent plus fréquentes pour respecter les objectifs d'échappement plus élevés durant les années de faible migration, mais l'industrie ne peut récupérer une plus-value accrue durant les années de fortes migrations. Quand les migrations sont abondantes, les transformateurs réaffectent la main-d'œuvre disponible à des produits à grand volume, mais à faible marge bénéficiaire, alors que quand les migrations sont très abondantes, l'insuffisance de la capacité de transformation permet l'échappement d'un plus grand nombre de poissons que prévu. Les navires mobiles à filets dérivants qui peuvent se déplacer vers les cours d'eau à migrations abondantes chaque année en bénéficient, mais les pêcheurs qui se spécialisent dans un district donné dans les flottes de petits bateaux et à filets fixes sont plus vulnérables durant les années de prises faibles ou nulles. [Traduit par la Rédaction]

Introduction

The sockeye salmon (*Onchorhynchus nerka*) fishery in Bristol Bay, Alaska, illustrates how economic and biological objectives can lead to different harvest policy recommendations. Despite its decades-long biological success, the salmon industry in Bristol Bay has experienced a period of economic losses in the most recent decade, prompting some to deem it a biological success but an economic failure (Hilborn 2006) and others to explore opportunities to improve the economic performance of the fishery (Link et al. 2003; Schelle et al. 2004; Bue et al. 2008). Fishery scientists, economists, and many in the fishing industry have long recognized that the economic performance of the Bristol Bay salmon fishery may not be optimized at maximum sustainable yield (MSY) levels; quantifying and conveying this has been a challenge. Management strategy evaluation (MSE) techniques are being increasingly applied to help stakeholders and managers understand how variability and uncertainty affect the evolution of stock levels and anticipated **biological** yield under different harvest policies. As the approach matures, best practices are being developed to guide the design of MSEs (e.g., Punt et al. 2016), with an emphasis on common sources of data, stock structure, and stock parameter uncertainty. We build on this work by developing an economically integrated MSE and use Bristol Bay salmon to identify fishery characteristics that warrant incorporating economic responses within MSEs to ensure economic objectives can be addressed alongside biological objectives and comprehensive advice can be conveyed to fishery managers and other stakeholders.

Over the course of six weeks each summer, an average of 37 million sockeye salmon return to the five fishing districts in Bristol Bay,

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Fig. 1. Map of Bristol Bay, Alaska. Crosshatched areas describe boundaries of terminal fishing districts, and gray labels indicate river systems of origin for each stock. Map was created with shape files from the Alaska Department of Fish and Game Anadromous Waters Catalogue and US Geological Survey National Hydrography Dataset and National Elevation Dataset. This figure was recreated from Cunningham et al. (2018). The Togiak River and associated terminal fishing district is not pictured and lies to the west of the Igushik River.

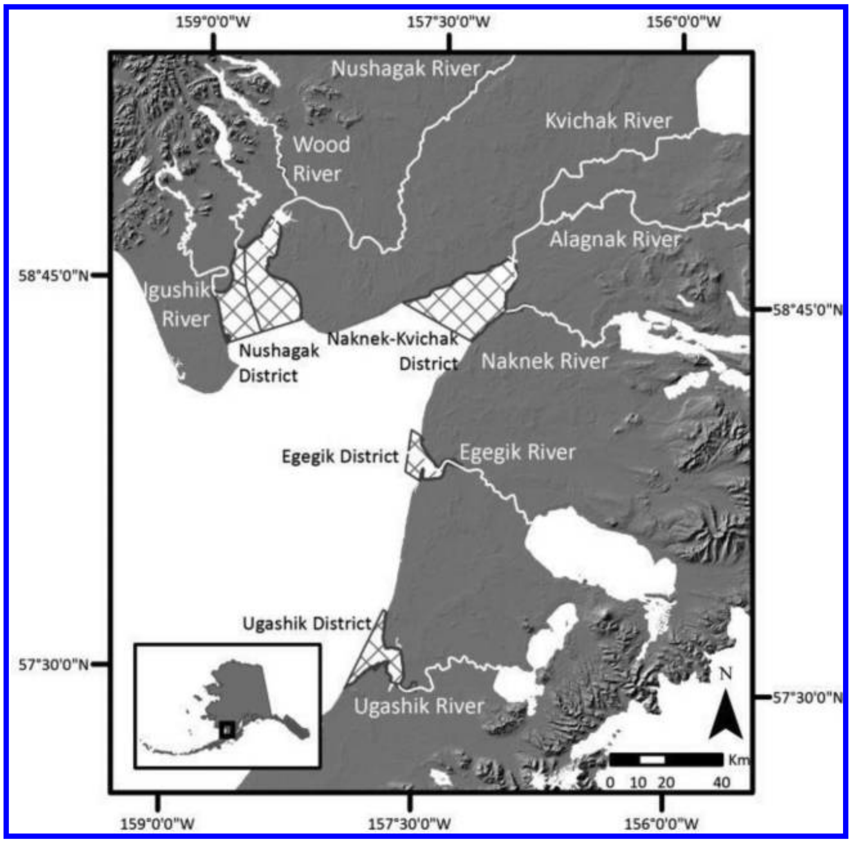


Table 1. Bristol Bay fishery summary statistics.

	Ugashik district	Egegik district	Naknek–Kvichak district	Nushagak district	Togiak district	Bay-wide
Mean run size, 1980–2012 (× 1000)	3 919	8 769	16 210	7 442	706	37 046
Standard deviation	1 593	4 320	8 145	2 944	270	
Mean catch, 1980–2012 (× 1000)	2 752	7 446	8 891	4 936	501	24 526
Standard deviation	1 396	4 139	5 188	2 271	213	
Mean escapement, 1980–2012 (× 1000)	1 167	1 322	7 319	2 506	205	12 520
Standard deviation	633	428	4 394	1 222	77	
Mean driftnet vessels*, 2002–2012	—	—	—	—	—	1 385
Mean driftnet permits, 2002–2012	354	552	696	555	110	—

*Permits are required to register to fish in a particular district, but starting in 2004, vessels could fish with two permits and extend their net length from 150 to 200 fathoms (1 fathom = 1.8288 m); thus, the number of vessels fishing in a district each year is not precisely known.

Alaska, supporting the most valuable wild commercial salmon fishery in the world. Up to 1500 driftnet vessels, with crews of up to four, jockey for position on each tide in which the Alaska Department of Fish and Game (ADF&G) declares the fishery to be open. They are joined by up to 900 shore-based set-net harvesting operations, who fish from prespecified riverside sites. Combined, this US$400 million fishery provides essential food, jobs, and economic activity in this isolated region of 6000 residents (Knapp et al. 2013).

The stocks exploited by this fishery spawn in nine rivers and are harvested in five single or mixed-stock terminal fishing districts (Fig. 1). Table 1 shows how each commercial fishing district contributes to the total run size and how run sizes fluctuate. To ensure sustainability, ADF&G establishes escapement goals — a desired range in the number of fish escaping capture in the commercial fishery and returning to the spawning grounds of each river — and opens fishing in the district at the mouth of each river only when escapement is at or above the historical arrival pace that supports meeting those escapement objectives. While larger escapements in most rivers are associated with higher expected future returns, historical observations at higher levels over the last 120 years are infrequent and outcomes are ambiguous. This variability is reflected in the precautionary nature of the status quo escapement goals, labeled "current sustainable escapement goals" (SEG) line in Table 2 (Baker et al. 2009). Escapement is carefully tracked within the season at enumeration sites (counting towers or fixed sonar sites) on each river, and the number of landed fish is estimated on a daily basis from the observed mass of

Table 2. Midpoint escapement targets (in thousands of sockeye) for the three alternative management strategies.

District	Stock	Current SEG	Proposed SEG	BEG
Nushagak	Igushik	225	300	291
	Wood	1100	1300	1550
	Nushagak	590	700	801
Naknek–Kvichak	Kvichak*	2000	2000	2000
	Alagnak*	320	320	320
	Naknek	1100	1450	1858
Egegik	Egegik	1100	1450	5242
Ugashik	Ugashik	850	1000	2602

Note: SEG, sustainable escapement goals; BEG, biological escapement goals.
*The Kvichak and Alagnak escapement targets are the same across three scenarios because these systems are not managed separately and targets did not vary across scenarios.

the catch; the Bristol Bay salmon fishery is perhaps the most intensively managed fishery in the world. It is Marine Stewardship Council certified.

As part of an every-3-year review process using the latest stock–recruit data, Fair et al. (2012) suggested that raising the escapement goals — considerably for Egegik and Ugashik — to the biological escapement goals (BEGs) in Table 2, would increase yield from the fishery. Harvest achieved by targeting these BEGs was expected to reflect more closely MSY. Alaska's Policy for the Management of Sustainable Salmon Fisheries specifies that, to the extent possible, salmon fisheries are to be managed for MSY, which depends on sufficient historical stock–recruit data to define MSY escapement (5 Alaska Administrative Code 39.222).

MSY is intuitively linked to good outcomes for harvesters and communities because greater fish availability means more fish to sell and therefore more fishing income and jobs. In addition, the higher escapement levels necessary to achieve MSY may provide alternative benefits to freshwater ecosystems and salmon-dependent predator communities (Levi et al. 2012). However, industry and local communities that depend on low catch variance and tax revenue have resisted this increase and encouraged more caution and incremental adjustments to escapement goals. In this highly variable fishery, increasing escapement goals has the potential to result in two side effects of questionable desirability from the perspective of fishery revenue. The first of these is a potential increase in the frequency of low run years in which less (or no) harvest will be allowed to achieve the higher escapement targets. Low run years are relatively frequent, and times of no harvest are devastating to rural Alaska communities, who are heavily dependent on salmon revenue. Second, there will be slightly more frequent very high run years. From a management perspective, the theoretical yield under the escapement goals proposed by Fair et al. (2012) would represent a huge potential harvest, but the fishery lacks the capacity to process potential catches during recent years of high runs. Therefore, many in the industry see increased escapement goals as increasing vulnerability in exchange for larger average runs that provide little or no upside for fishery participants. ADF&G thus proposed a more modest change, the "proposed SEG" line in Table 2. Bue et al. (2008) showed that economic profitability was influenced by limits on processing and harvesting capacity, and industry intuitively understood that bigger runs do not translate directly into greater economic performance.

Industry responded to Fair et al.'s (2012) proposal by convincing regulators to first examine the economic impacts of moving from the existing goals to four alternatives, three of which are listed in Table 2, before revising the escapement goals. Industry was provided 2 years to work together with ADF&G and other scientists and recommend escapement goals that take into account the economics of the fishery. To ensure meaningful inputs to our models and realistic alternative escapement goal policies to examine, the study team was guided by a nine-person advisory panel of individuals with expertise in Bristol Bay fishery management, harvesting and processing, and the regulatory processes.

Whether increasing (average) run size in accordance with MSY aligns with the goals of supporting the harvesters and communities that participate in this fishery depends on the industry's ability to catch and process during very large run years (Bue et al. 2008). Current bay-wide processing capacity is around 1.8 million fish per day. Since salmon is landed fresh and cannot be held for long without processing, a day of high catches has two consequences for processors. First, they must curtail the flow of fish coming to their plants by placing their contracted fleets "on limits", declaring that they will not buy more than a fixed number pounds from each vessel during an opening. Additional fish returning during this period escape, but provide no value to the fishing industry in the current year. Limits are not popular among the fleet, and processors that are more frequently forced to put their fishermen on limits have a harder time contracting vessels to their fleet in the future. Nevertheless, limits are clearly part of the processors' strategy for handling considerable interannual volatility; they could build plants to accommodate the maximum run size, but instead there is a persistent pattern of at least 2 days-on-limits, in roughly 2 of every 5 years. This suggests that the value of these additional fish that could be captured during limited periods is not sufficient to cover the cost of maintaining excess processing capacity in the remaining 3 of 5 years.

The second way processors handle daily gluts is by accelerating their processing rates. If input markets were fluid, the plants would hire temporary labor and purchase other inputs to deal with the high availability of fish. However, because Bristol Bay is geographically isolated, plants must commit to staffing and stocking levels based on preseason run size forecasts, supplied by ADF&G and the University of Washington. Physical inputs are barged to the region in spring, and laborers are flown up before the season; additional supplies of neither can be accessed on a relevant timeline once the actual extent of the fish run is realized. Instead, processors accelerate fish utilization by redeploying labor onto product lines that can process more fish per effort hour, from labor-intensive fillet lines to head-and-gut or canning lines. These products, particularly if produced in large quantity during a season, are generally lower margin than more labor-intensive products. Thus, product composition depends on the observed run size and timing, so processors cannot project the markets into which they will be selling and thus the prices they will receive per pound of landed fish.

The bioeconomic picture of Bristol Bay is a complex one, where the value of the catch is limited by available fish in low-run years, but also by processing capacity in high-run years. The value of fish on peak run days is eroded through processing into lower value products; in the highest run years, this value is entirely dissipated because capacity constraints allow it to escape. As a result, increases in average run size that also increase the variance of potential catch may not result in more fish being landed and processed, leading some authors to suggest a constant harvest management strategy (Steiner et al. 2011). Further, increasing catch variability is not distributionally neutral because, while individual-river variability can be mitigated by switching to other rivers during the season, harvesters differ in their ability to do this. State-of-the-art driftnet vessels can easily move among river systems to those with more returns, but "homesteaders" who traditionally fish only one district and set-net harvesters generally cannot.

Understanding how three proposed escapement goal policies attain economic and community objectives for the fishery therefore requires not only modeling the stock but also evaluating how participants in the harvest and postharvest sectors react to run size variability. Harvests, and thus stock size and fishery benefits, will be based on processors' long-run plant scale choices, which will dictate the size of the work force chosen to operate the lines they can keep busy most days of the season, and in turn constrain the product mix, which is determined by the shape and timing of the run as much as its size. This paper describes an integrated bioeconomic MSE that quantifies the trade-off between the average yield and the variance in yield, which provided regulators with guidance on designing harvest policies for environments where production variability is a major factor in shaping outcomes for industry and fishing communities.

Methods

Our MSE builds upon models of four key processes. First, we describe the age-structured stock–recruit model, which uses historical data to specify the relationship between escapement and subsequent returns of sockeye in future years. This recruitment model interacts with a management model that simulates managers' decisions of which rivers to open and when, based on the available in-season information; this relates intended escapement goals to predicted escapement, capturing management imprecision. Second, we model processors' production decisions on three timelines: the long-run choice of plant scale; the preseason choice of staffing level, based on run size forecasts; and the daily choice of product form, based on daily landings. Third, we model the annual price flexibility of the dominant salmon products produced in Bristol Bay. Finally, we link processor revenue and product mix to a division of revenue between processors and harvesters. These models are then used as the basis for 100-year forward simulations of the stock and processing industry, to project the mean and variance of fishery revenues to key participants under the alternative escapement goal policies.

Stock–recruit model

We use the biological MSE framework developed in Cunningham et al (2015*b*) to model daily catch, escapement, and run size for eight major sockeye stocks in Bristol Bay: the Alagnak, Kvichak, and Naknek stocks in the Naknek–Kvichak district; the Wood, Nushagak, and Igushik stocks in the Nushagak district; and the Egegik and Ugashik stocks in their eponymous districts. Here we briefly summarize the key features of the model.

To simulate the spawner–recruit dynamics for each river system, Ricker-type spawner–recruit models are fit to data reconstructed by Cunningham et al. (2018) for years 1963–2013 (eq. 1). The expected recruitment, $R_{y,p}$ of each stock p from brood year y is parameterized with $\alpha_{y,p}$, the maximum productivity in the absence of density-dependent compensation, $\beta_{y,p}$, the equilibrium biomass, and $\sigma_{y,p}$, the standard deviation of log-normally distributed process uncertainty.

$$\begin{aligned} R_{y,p} &= S_{y,p} \times \mathrm{e}^{\left[\alpha_{y,p}\left(1-\frac{S_{y,p}}{\beta_{y,p}}\right)\right]} \times \mathrm{e}^{\varepsilon_{y,p}} \\ \varepsilon_{y,p} &\sim \mathrm{N}(0, \sigma_{y,p}) \end{aligned} \tag{1}$$

Three versions of the Ricker model are used to simulate future recruitment patterns for Bristol Bay stocks. The first assumes production dynamics are best approximated by two Ricker functions representing high and low production regimes, where regime transitions are treated as a first-order Markov process and regime transition probabilities are estimated for each stock using Bayesian methods. This model is used to simulate the recruitment process for the Kvichak, Naknek, Egegik, Ugashik, Wood, and Igushik stocks. Second, a Bayesian Ricker model, assuming a single production regime, is used to simulate the recruitment process for the Alagnak stock. Third, a maximum likelihood Ricker model is adopted for the Nushagak stock, given the absence of suitable prior information on equilibrium (unfished biomass); see Cunningham et al. (2015*a*) for further detail.

Annual abundance levels are determined for each of the four main harvested age classes, $a \in \{1.2, 1.3, 2.2, 2.3\}$, where $c.d$ denotes a fish that spent c years in fresh water before spending d years at sea before returning to spawn. Each of the eight populations are simulated from 2014 to 2113. The observed escapements from 2008 to 2013 are used to initialize the simulation. Recruitment from brood year y, population p, and simulation s, $\hat{R}_{y,p,s}$, is predicted based on the spawning abundance and the estimated regime-specific spawner–recruit relationships. The number of returning age a fish in calendar year t for each population p in each simulation s is given by

$$A_{t,p,s,a} = \hat{R}_{y,p,s}\,\phi_{p,a} \tag{2}$$

where $\phi_{p,a}$ is the mean share of stock p's return that is age a (see Table A1). Spawners for year y are then

$$S_{y=t,p,s} = \sum_{a\in\{1.2,1.3,2.2,2.3\}} A_{t,p,s,a} - C_{t,p,s} \tag{3}$$

the number of returning adults minus the estimated catch, $C_{t,p,s}$, from the management and production models discussed below.

Management model

Managers in Bristol Bay face several challenges in achieving their escapement targets each season. To balance harvest across early- and late-returning subpopulations, managers attempt to spread harvest across the season to impose equal harvest rates on all stocks harvested within mixed-stock commercial fishing districts. However, actively managing commercial fishing effort relies on judgement of what cumulative escapements should be achieved through a given day of the season. This is confounded by variation in both run size and arrival timing. Managers open and close individual districts, or river-specific "special harvest areas", for fishing on a daily basis, but using lagged information about fish migrating from the commercial fishing district at the river mouth to upriver escapement enumeration sites. Further, river-mouth abundances and catches are a mixture of stocks from several component river systems, especially on the east side.

The management model, described in Cunningham et al. (2015*b*), incorporates three key implementation uncertainties. For each year in the forward simulation, the management model first takes the annual run size by stock from the biological model and partitions them into daily stock-specific arrivals to each district. The arrival timing is randomly drawn from patterns observed during 1963–2008. The number of fish entering each fishing district in each simulated year t is

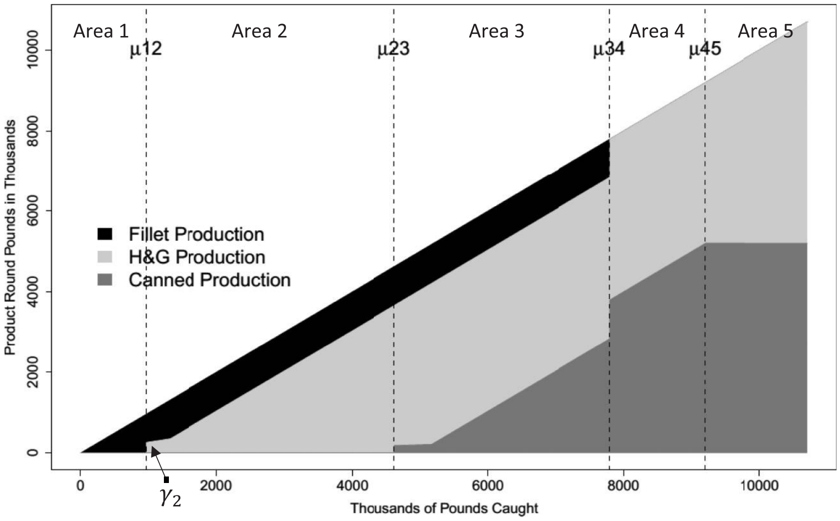
$$E_{t,p,s,d} = P_{t,p,s,d} \sum_{a\in\{1.2,1.3,2.2,2.3\}} A_{t,p,s,a} \tag{4}$$

the product of $A_{t,p,s,a}$, the annual abundance of arriving sockeye by stock s, and $P_{t,p,s,d}$, the proportion of total annual return of population p arriving on day d.

The simulated managers select which fisheries to open on each day of the season by comparing observed cumulative escapement for each stock to the target cumulative escapement based on available information through that date. They know that the number of fish entering the fishing district, less the harvest on each of the preceding days of residency r, equals the number of fish leaving the district on day d:

$$L_{t,p,s,d} = \sum_{r=1}^{2} (E_{t,p,s,d-r} - H_{t,p,s,d-r}) \tag{5}$$

Fig. 2. The modeled relationship between daily catch volume and processed product mix (1 pound = 0.453 kg). At low daily landings (Area 1), plants produce labor-intensive, high-margin fillets. As landings increase beyond μ_{12}, they add labor and introduce headed and gutted frozen fish (H&G) production, and at μ_{23} they add lower-margin canning production. At μ_{34}, the fixed labor supply is reallocated from filleting to canning, and beyond μ_{45} all capacity within the bay is exhausted and processors use tender vessels to ship fish to H&G plants outside the region.



The number of fish leaving the district is adjusted by the number of days it takes to get from the fishing district to the counting site, providing lagged information to the simulated manager in deciding whether to open the district or not. If the cumulative escapement on day d exceeds the expected escapement through that day necessary to meet the escapement target, given the average arrival distribution for that stock, the fishery is opened. If the cumulative escapement on a given day any stock harvested within a mixed-stock fishery is below the target level, the fishery is closed the subsequent day.

When the manager opens a fishery, f, daily harvest is given by

$$H_{t,p,s,d} = E_{t,p,s,d} h_{f,p} \tag{6}$$

where $h_{f,p}$ is the stock-specific harvest rate in each possible spatial fishery opening, f. This parameter takes into account interception rates for each commercial fishing district, section, and special harvest area (Tables A2 and A3) and is tuned through an iterative process of comparing management model predicted escapement outcomes with observed escapements for years 1963–2008. Importantly, this harvest rate is independent of the number of vessels in the district; regressing total daily harvest on active vessels and reconstructed district-specific abundances reveals that the ability to harvest the available fish is independent of fishing effort. Because harvesters participate in a derby with as much as five times the required capacity (Link et al. 2003; Gho 2015), the data suggest there is always enough capacity to harvest all biologically available fish.

Processor product form choice

The daily harvests from the management model affect processors' choice of which products to produce, constrained by the processors' preseason choice of how much labor to transport to the region, and the long-run decisions regarding processing capacity. We first describe the model of daily product form choice and then capture how processors back out their seasonal labor and plant capacity choices.

Daily product form choice

Cans, headed and gutted frozen fish (H&G), and frozen fillets represent 95% of the product value from Bristol Bay (Knapp et al. 2013). The choice of product form is driven by total landings each day; the fixed labor pool can direct more fish to minimally processed canned and H&G products than into higher-priced, more intensively handled fillets. Thus, predicting economic effects requires predicting these daily product form decisions, which are a function of physical capital, and the quantity of labor that is brought into Bristol Bay in any season, based on the preseason run size forecast. However, developing a daily decision model is complicated by the fact that product form data are reported for only total annual production. We therefore build a daily bay-wide product form model based on factors that interviewed processors indicated were important, calibrate it to match observed production quantities in recent years, and validate our calibration with processing representatives on our advisory panel.

We model processors' daily production decisions with a series of threshold points in daily bay-wide landings. Based on Commercial Operator's Annual Report (COAR) production data and advice from processing experts, we model a bay-wide total of eight fillet, 16 H&G, and 26 canning lines. The daily processing capacity of a standard fillet, H&G, and canning line is 120, 250, and 200 thousand pounds of whole fish (approximately 55, 114, and 91 thousand kg), respectively. In addition, at peak season, processors often have the capacity to ship a total of 1.5 million pounds (682 thousand kg) of whole fish per day to plants outside the Bay (all H&G) using contracted "haul-out" vessels. Whole fish average 6 pounds (2.73 kg). Fillet, H&G, and canned products yield 0.5, 0.72, and 0.65 of the whole fish mass, based on estimates from Alaska Office of Fisheries Development (DCCED). Running all fillet, H&G, and canning lines at full capacity requires 26%, 42.5%, and 57.5% of the current maximum labor force, respectively, and based on processor interviews, preseason staffing does not exceed that needed to run all canning and H&G lines concurrently, leading to a baseline maximum staffing of $N_{\max} = 3390$.

The model is calibrated using the daily landings and annual aggregate product mix from 2008, when fillet lines became prevalent, to 2013. We divide the range of possible daily catch values into five different product mix regions, denoting thresholds between regions as μ_{12}, μ_{23}, μ_{34}, and μ_{45} (Fig. 2). Intuitively, processors produce the most profitable and labor-intensive product, fillets, when daily catch is low (less than μ_{12}). When daily catch exceeds the daily production capacity of the filleting lines, some

Table 3. Calibrated parameters for relationship between daily volume and product mix.

		Daily volume (whole fish)	
	Product mix threshhold	(pounds, × 1000)	(kilograms, × 1000)
Slope of fillet in area 2 (γ_2): 0.73	μ_{12}	960	436
Slope of canned in area 3 (γ_3): 0.05	μ_{23}	4622	2101
Slope of canned in area 4 (γ_4): 0.39	μ_{34}	7796	3544
	μ_{45}*	9200	4182

*When daily landings exceed μ_{45}, canning capacity is fully utilized, and additional fish is tendered to H&G plants outside Bristol Bay.

labor is diverted to H&G (between μ_{12} and μ_{23}). Since the fish caught are split between H&G and fillet, we estimate the proportion of fish processed into fillets, γ_2, which is constrained by the fillet line capacity. As daily landings increase further, processors direct resources to canning lines, producing a mixture of all three products (between μ_{23} and μ_{34}). Assuming processors produce fillets at maximum capacity in this region, we estimate the proportion of the remaining fish that is canned, γ_3. When daily landings exceed the point where producing all three products is no longer feasible due to labor constraints (between μ_{34} and μ_{45}), they pull labor from fillets and we estimate the proportion of canned products, γ_4, which is constrained by both the H&G and canning production capacity. Finally, when daily landings exceed μ_{45}, canning capacity is fully utilized, and additional fish is tendered to H&G plants outsize Bristol Bay.

Since μ_{12} is determined by the total fillet production capacity across processors (960 thousand pounds (436 thousand kg) of whole fish per day), and the joint production capacity limit of canning and H&G determine μ_{45} (9200 thousand pounds (4182 thousand kg) of whole fish), we only need to calibrate μ_{23} and μ_{34}, in addition to the slope parameters. Using observed daily landings from 2008 to 2013 as inputs, five parameters are calibrated such that the sum of absolute differences between observed annual production and predicted annual production by product form is minimized with γ_2, γ_3, and γ_4 equal to 0.73, 0.05, and 0.39 and μ_{23} and μ_{34} equal to 4622 thousand and 7796 thousand pounds (2101 thousand and 3544 thousand kg), respectively (Table 3).

Long-run plant scaling

While the product mix thresholds in the daily model reflect recently observed levels in bay-wide capitalization, if changing biological management led to consistently larger run sizes, any associated changes in harvests would be expected to stimulate investments (or disinvestments) in processing capacity relative to current conditions. However, it is not optimal for processors to build plants so large as to be able to process the maximum possible run size, as evidenced by plants putting their fishermen on daily landings "limits" for 2 or more peak-run days in about 40% of recent years.

Modeling possible processor responses to changes in future runs is difficult because the limited annual-level data are confounded by the emergence of aquacultured salmon products, which have transformed the market for wild salmon products (Knapp et al. 2007). Rather than building a statistical model that attempts to control for such confounding variables on few observations, we develop a calibration to predict future changes in processing capacity based on the average days during the season where processing capacity constrains catch. Processors face strong incentives to limit the number of times they must put their fishing fleets on limits during any season. Maintaining a consistent ex-vessel market is important to attracting a fleet of productive highliners in future seasons, and processors wish to maintain market share of their wholesale products. Preseason forecasts and recent years' harvests are used by processors to gauge their short- and long-term investments in capacity to minimize use of limits on their fleets within the coming season.

Since 2000, processors have averaged 2 days-on-limits per season, providing a revealed preference benchmark for striking a balance between processing enough fish to provide markets to harvesters, and to supply wholesale markets, and the cost of maintaining lines that may not get used in every season. To evaluate alternative capitalization strategies, we scale up the daily capacity and threshold values in Fig. 2 by a factor δ of daily processing capacity in 2014, reflecting a percentage increase in the number of each type of processing line. This scaling applied across all products (i.e., fillet, H&G, and canned) such that thresholds μ_m where $m \in \{12, 23, 34, 45\}$ are modified to $\bar{\mu}_m = \mu_m(1 + \delta)\forall m$ and $\bar{N}_{\max} = (1 + \delta)N_{\max}$; slopes remain unchanged.

Preseason staffing

Given a fixed plant size, processors can scale their costs to the anticipated run size at the seasonal level by controlling the quantity of labor hired. Owing to the remote location of Bristol Bay, workers, like other processing inputs, have to be shipped into the region before the fishing season starts; they live in dormitories on site. Only 1.7% to 3.5% of processing employees are local residents. Since it is costly to fly in and house more workers than necessary or to have insufficient labor to process harvested fish, processors carefully consider how many workers to hire prior to the start of a season. We predict the number of workers hired in each year t, N_t, as a function of the preseason forecast in thousands of fish.

$$(7) \qquad N_t = \beta_{11} + \beta_{12}\text{PreseasonForecast}_t + \epsilon_t$$

Equation 7 is calibrated using annual observations from 2001 to 2012 from the Alaska Department of Labor and Workforce Development and the University of Washington Forecast Reports for Bristol Bay salmon. We use $\beta_{11} = 1209$ and $\beta_{12} = 0.074$, suggesting a forecast of an extra million fish leads processors to bring an additional 74 workers.

Pricing model

Since the alternative escapement goals may alter the run sizes, and thus catch and product composition, it is necessary to determine the responsiveness of global-market wholesale prices for each product to changes in Bristol Bay production quantities. This is challenging because the data available for each product form are different and, in some cases, limited. We consider the wholesale markets for canned salmon and filleted and H&G salmon separately (Asche et al. 1998; Knapp 2004).

We model price responsiveness with a single price equation, rather than a supply–demand system. Since prices are observed annually, there is little data (fewer than ten observations in some cases) to support a model with more parameters. Further, quantity is exogenous because product form is determined during the season based on daily landings, and prices for most wholesale transactions are not negotiated until after the season closes and processors know what they can and must sell.

Table 4. Coefficient estimates and summary statistics for model equations.

Equation	β_{n1}	β_{n2}	β_{n3}	β_{n4}	Observations	R^2
7	1209.41 (802.72)	0.0738* (0.0237)	—	—	12	0.4936
8	3.6140** (1.1048)	−0.2503* (0.1142)	0.5186** (0.0878)	0.0183 (0.0649)	21	0.8795
9	0.3811 (1.009)	−0.1747* (0.0843)	1.0412** (0.1516)	—	21	0.8094
10	3.4625** (1.1732)	−0.2183** (0.0688)	0.9867** (0.1444)	—	13	0.7876
11	1.0103** (0.3091)	−0.0431 (0.0240)	0.9279** (0.1809)	—	13	0.7602
12	0.0782 (0.1136)	0.8224** (0.1398)	—	—	11	0.7936
13	5.0794** (0.5703)	0.7254** (0.0379)	—	—	11	0.9760
14	−1.258e+07** (1.917e+06)	0.5449** (0.0524)	0.6886** (0.0410)	0.3026** (0.0781)	10	0.9983

Note: Standard errors are given in in parentheses. **, $p < 0.01$; *, $p < 0.05$.

Wholesale price of canned sockeye

Knapp (2004) argues that the wholesale price of canned sockeye is driven by the available supply in the current season. We use data from the 1980–2010 National Marine Fishery Service (NFMS) annual export data set and annual COAR reports (NFMS and ADF&G COAR). To control for demand effects on the wholesale prices in Bristol Bay, we first estimate the export price of canned sockeye (ECP_t) as a function of exported canned sockeye quantities (ECQ_t), export price of canned pink salmon (*Oncorhynchus gorbuscha*) (ECPP_t), and Bristol Bay canned production (BBCQ_t).

$$\text{(8)} \qquad \ln(\mathrm{ECP}_t) = \beta_{21} + \beta_{22}\ln(\mathrm{ECQ}_t) + \beta_{23}\ln(\mathrm{ECPP}_t) + \beta_{24}\ln(\mathrm{BBCQ}_t) + \nu_t$$

It is necessary to include pink salmon in this relationship as past price–quantity relationships are influenced by the prices of substitute products, and omitting this relationship would lead to biased estimates of price responsiveness. Then we use the predicted value for ECP_t to estimate

$$\text{(9)} \qquad \ln(\mathrm{BBCP}_t) = \beta_{31} + \beta_{32}\ln(\mathrm{BBCQ}_t) + \beta_{33}\ln(\mathrm{ECP}_t) + \epsilon_t$$

where log wholesale Bristol Bay canned price (BBCP_t) is modeled as a function of log Bristol Bay canned sockeye production (BBCQ_t) and predicted log ECP_t. The first stage regression controls factors that may influence the demand for Bristol Bay canned sockeye; this isolates the own-product quantity effect on price, which lets us predict how prices will change with quantity at average price levels of substitutes. The second stage regression takes the predicted first stage results to estimate how Bristol Bay prices respond to the quantity produced. This process allows us to correct for any inconsistencies that may arise from estimating inverse supply and inverse demand equations simultaneously. Given the small sample sizes, we report nominal estimates as calibration values for use in the forward simulation, rather than as complete econometric demand models, though goodness of fit and standard errors are reported in Table 4. With the data in 1982 dollars, the calibration values for β_{21}, β_{22}, β_{23}, and β_{24} are 3.61, −0.25, 0.52, and 0.02, and the values for β_{31}, β_{32}, and β_{33} are 0.38, −0.17, and 1.04, respectively (Table 4). This suggests that Bristol Bay canned sockeye prices fall 0.17% with a 1% increase in production.

Wholesale prices of filleted and H&G sockeye

While the demand for frozen sockeye products has been studied extensively (Asche 1997; Asche and Wessells 2002; Williams et al. 2009), that work has not treated H&G and fillets as separate products. This is likely because filleting only became common in Bristol Bay in the early 2000s, so there are only a limited number of annual observations. NMFS trade data do not distinguish fillets and H&G products, so we use the 2001–2013 data on prices and quantities from the Alaska Department of Tax Revenue and NMFS annual import prices (ATR and NMFS).

The annual mean wholesale price of Bristol Bay H&G (BBHGP_t) and Alaska fillet (AFP_t) are predicted by estimating eqs. 10 and 11 simultaneously, where we use Bristol Bay annual H&G production (BBHGQ_t) and import price of frozen farmed Atlantic salmon fillet (IP_t) as two predictors for Bristol Bay H&G wholesale prices and Alaska fillet production (AFQ_t) and IP_t as explanatory variables for Alaska fillet wholesale prices. We use the wholesale Alaska fillet price, rather than Bristol Bay prices, for eq. 11 because the Bristol Bay time series does not have the three firms producing fillets required for data to be nonconfidential.

$$\text{(10)} \qquad \ln(\mathrm{BBHGP}_t) = \beta_{41} + \beta_{42}\ln(\mathrm{BBHGQ}_t) + \beta_{43}\ln(\mathrm{IP}_t) + \epsilon_t$$

$$\text{(11)} \qquad \ln(\mathrm{AFP}_t) = \beta_{51} + \beta_{52}\ln(\mathrm{AFQ}_t) + \beta_{53}\ln(\mathrm{IP}_t) + \nu_t$$

This technique, a seemingly unrelated regression, is adopted because we believe that two equations are related through correlation in the error terms. Frozen farmed Atlantic salmon (*Salmo salar*) fillet is treated as the primary substitute for frozen wild Pacific sockeye products (cf. Williams et al. 2009; Asche et al. 1998). The estimates for β_{41}, β_{42}, β_{43} are 3.46, −0.22, 0.98, and the estimates for β_{51}, β_{52}, β_{53} are 1.01, −0.04, and 0.93, respectively (Table 4). This suggests prices fall 0.22% for a 1% increase in Bristol Bay H&G production.

To predict the wholesale price for Bristol Bay fillets specifically, we need to establish the relationship between Alaska and Bristol Bay wholesale price and quantities:

$$\text{(12)} \qquad \ln(\mathrm{BBFP}_t) = \beta_{61} + \beta_{62}\ln(\mathrm{AFP}_t) + \epsilon_t$$

$$\text{(13)} \qquad \ln(\mathrm{AFQ}_t) = \beta_{71} + \beta_{72}\ln(\mathrm{BBFQ}_t) + \epsilon_t$$

where the wholesale Bristol Bay fillet price (BBFP_t) and quantity (BBFQ_t) are linked as proportions of Alaska fillet quantity and price. We estimate the relationships using annual ATR data from 2001 to 2013. The estimates for β_{61}, β_{62}, β_{71}, and β_{72} are 0.08, 0.82, 5.08, and 0.73, respectively (Table 4). Combining equations, Bristol Bay fillet prices fall 0.02% with a 1% increase in Bristol Bay production, likely reflecting fillets produced in Bristol Bay are a small part of a market dominated by foreign-processed sockeye fillets and aquaculture.

Ex-vessel prices

Because of different processing costs, different product compositions may lead to different shares of wholesale revenue going to harvesters as payments for fish. Knapp (2013) argues that the share of aggregate wholesale revenue that is passed to harvesters has been stable since the early 2000s. Since our focus is on how changes in product mix arising from the profile of daily harvests within Bristol Bay affects ex-vessel prices, we modify Knapp's model to capture any variation associated with product mix decisions, allowing for different (unobserved) profit margins by product form rather than using simultaneous equation equilibrium model of supply and demand developed by Williams et al. (2009).

$$\text{(14)}\quad \begin{aligned} &\mathrm{EP}_t \times (\mathrm{BBCQ}_t + \mathrm{BBHQ}_t + \mathrm{BBFQ}_t) = \beta_{81} + \beta_{82}\mathrm{BBCP}_t \\ &\times \mathrm{BBCQ}_t + \beta_{83}\mathrm{BBHQ}_t \times \mathrm{BBHP}_t + \beta_{84}\mathrm{BBFQ}_t \times \mathrm{BBFP}_t + \epsilon_t \end{aligned}$$

We first estimate ex-vessel values (where EP_t is ex-vessel price) as a function of processor wholesale values by product form using annual ATR data from 2001 to 2013. To recover ex-vessel prices for the season, we divide the ex-vessel values by predicted aggregate processor production quantities from the daily product form choice model. After covering fixed costs, we find harvesters are paid 54.5% of canned wholesale revenue, 68.9% of H&G revenue, and 30.3% of fillet revenue.

Forward simulation

To evaluate impacts of the alternative escapement goal policies, we use the biological, management, and economic models to simulate the future, from a starting point of recent stock-specific escapements and current global market conditions. Reported results for these "forward simulations" average over 1000 iterations describing uncertainty in future production dynamics for the period 2014–2113 for each of the three different escapement goal policies.

An iteration of the simulation starts with determining the total number of fish returning for each stock, based on previous years' escapements through the biological model. We then generate a preseason forecast observed by processors, based on the actual run size and a log-normally distributed observation error calibrated to the scale of recent preseason forecast errors:

$$\text{(15)}\quad \begin{aligned} &\mathrm{PreseasonForecast}_t = \mathrm{Actual\ run\ size}_t \times \eta_t \\ &\eta_t \sim \mathrm{logNorm}(0.0204,\ 0.2184) \end{aligned}$$

From this, we use eq. 7 to generate the number of workers brought into Bristol Bay for the coming season. The predicted number of workers hired in year t, $\hat{N}_t$, is truncated at $\overline{N}_{\max}$ and used to scale product thresholds points μ_m, where $m \in \{12, 23, 34, 45\}$, such that $\hat{\mu}_{mt} = \frac{\hat{N}_t}{\overline{N}_{\max}}\overline{\mu}_m$.

The timing and duration of the run is matched to a random historic observation. Daily catch and escapement, based on simulated management performance, are generated for the annual return. To operationalize the daily production model, we add two intertemporal considerations that processors emphasized play a role in their daily decision-making. First, we calculate a 3-day moving average process of the daily catch from the management model. This reflects processors' ability to carry over some landings from one day to the next. Second, we capture a small, inelastic demand market for canned salmon by ensuring a minimal quantity is produced. We establish a behavioral rule of thumb that if canned production is lower than 5.65 million pounds (2.57 million kg) of whole fish, the minimum observed in the period 1984–2010, by 11 July, all the fish that are caught after that date will be canned until 5.65 million pounds of whole fish are processed into cans. The chosen date ensures this product switch happens only after the peak of the season, when it would not happen based on daily landings.

Next, we capture events where daily catch exceeds processing capacity. Even though we smooth daily catches with a 3-day moving average, we still observe situations where the smoothed daily catch exceeds daily processing capacity. In the field, the processors put harvesters on daily landings limits. We represent the biological implications of daily harvester limits by allowing the amount of fish exceeding the processing capacity to become additional escapement, which influences future returns through the recruitment simulation model. This feature incorporates economic decisions as a driver of biological outcomes within our integrated MSE model.

Table 5. Mean number of days-on-limits at a range of increases in daily processing capacity.

% increase in daily processing capacity limit	Current SEGs	Proposed SEGs	BEGs
No increase	3.76	4.35	4.34
15%	2.20	2.71	3.18
20%	1.90	2.31	2.85
25%	1.55	1.97	2.55
35%	1.09	1.42	2.03
40%	0.91	1.21	1.81

Note: Means from 1000 simulations of 100 years each; we used the final 74 years of each 100-year simulation to compute the mean.

Given daily catch from the MSE framework and the number of workers predicted from the preseason staffing decision model, the within-season processor model predicts daily production of fillets, H&G, and cans using the parameter values presented in Table 3. Given annual aggregate production of each product, we calculate wholesale and ex-vessel prices using eqs. 8–14, with parameter values reported in Table 4. The forecasts adopt the most recent 5-year mean export price of canned sockeye, $5.81 per pound ($12.78 per kg), and import price of frozen Atlantic salmon fillets, $1.94 per pound ($4.27 per kg), as constant in the forward simulations. To ensure that harvesters do not end up receiving negative payments, we stipulate that processors pay harvesters a minimum of 10 cents per pound (22 cents per kg) of whole fish. We then convert values to 2013 US dollars (inflating by 2.44), completing an iteration of the forward simulation. This is repeated 1000 times to evaluate each escapement goal scenario, given uncertainty in the biological and management processes.

Long-run plant scale calibration

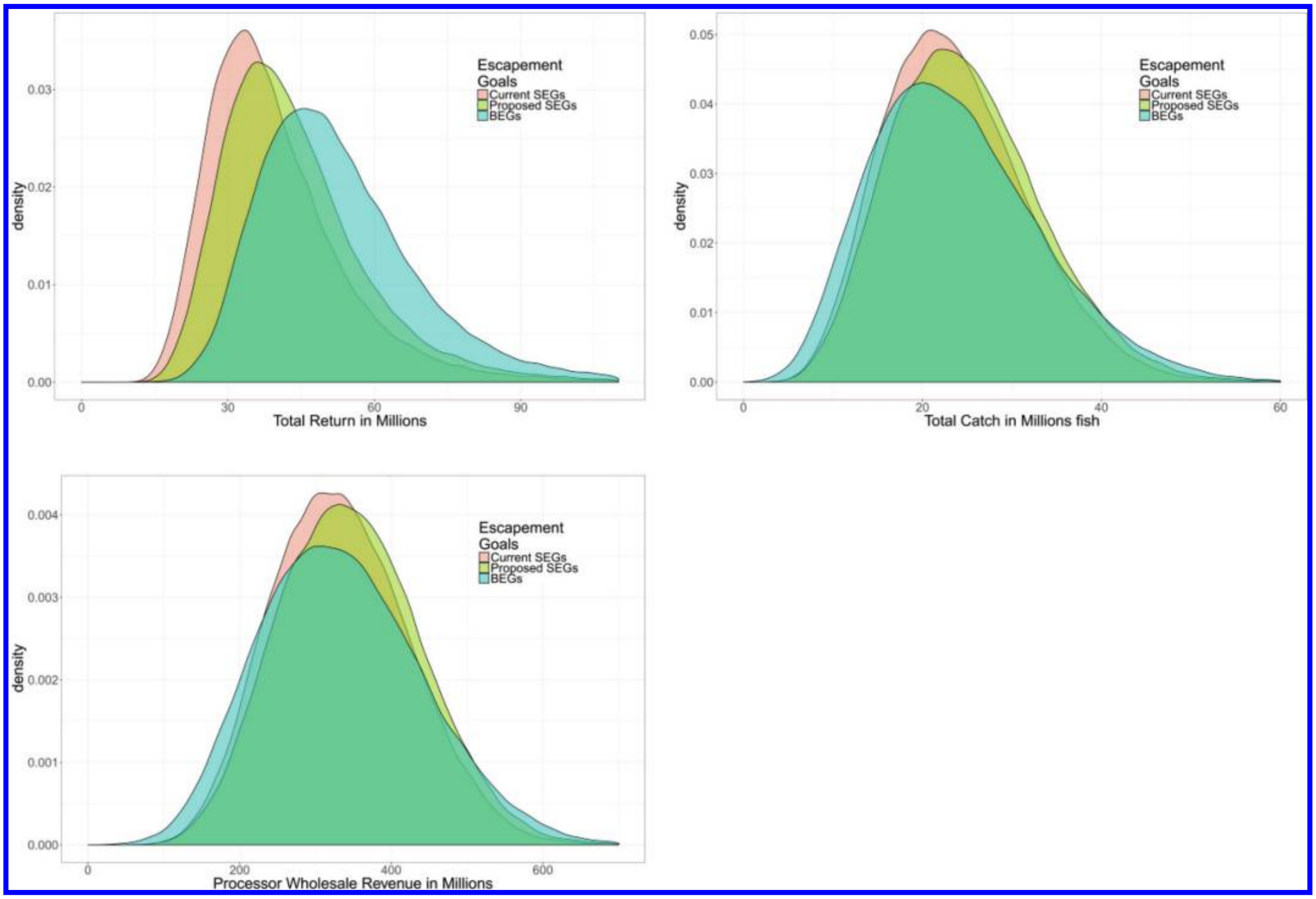
The remaining calibration is to determine the level of long-term capital investment that meets the 2 days-on-limits rule of thumb. We run the above model at δ equal to 0%, 15%, 20%, 25%, 35%, and 40%, and drop 2015–2040, a biological transition period, to capture a steady state result. A 20% increase (for current SEGs), a 25% increase (for proposed SEGs), and 35% increase (for BEGs) in processing capacity best fit the selection criterion described above (Table 5). Predicting a 20% increase in capacity under current policy corroborates our model, as at the time of the study a new plant for Silver Bay Seafoods was under construction, increasing baywide processing capacity by more than 15%. When we calculate the mean number of days-on-limits for a season across 100 simulations, we did not include years where daily processing capacity is exceeded due to insufficient labor, because that is not a long-run capitalization problem.

To compare the alternative escapement goal scenarios, we examine the distributions of catch and wholesale and ex-vessel revenues in steady state, excluding transitional years 2015–2040. We do not attempt to forecast decadal- or century-scale trends in global seafood markets, but rather compare the alternative escapement goal policies under current conditions.

Results

The model predicts that higher escapement goals are expected to lead to higher average run sizes across rivers. However, the interannual variation of the run size also increases, as shown in Fig. 3*a* and the top section of Table 6. Much of the increase in mean is driven by a long right tail of infrequent but very large runs, a structure that has important implications for processors and harvesters. The right-skewed distribution of run size is driven

Fig. 3. Distributions of run size, catch, and wholesale revenues. Note that thin right tails of the density graphs have been truncated. [Colour online.]



by lognormally distributed process variation in recruitment and reflects the high level of variation in production observed for most stocks in the past. The BEG policy has the highest mean and highest interannual variance, followed by the proposed SEGs, and finally the current SEGs. Comparing the size of the changes from each scenario reveals a trade-off between the mean and variance of the run size.

While average run sizes are higher under the proposed SEG and BEG policies, they do not translate into higher catches or processor revenues. Figures 3*b*, 3*c*, and the second and third sections of Table 6*a* both suggest similar average catches and processor revenues compared with the status quo SEG policy. For the (high escapement) BEG scenario, we predict a 1.33% decrease in the median catch, the same mean, and a 48.8% increase in interannual catch variation. While BEGs represent MSY in Fair et al.'s (2012) model, they do not increase average harvests and do increase variability in our state-transition model, which may have slightly different MSY escapements. Two competing pressures of higher escapement goals explain this divergence between run size and catches. First, higher escapement goals require that more returning fish be preserved for escapement, rather than catch, so in low-run years, catches are lower. Second, the more frequent high-run years are not frequent enough to support investment in the capacity to process all the additional fish available for catch. The value of this fish is thus eroded because processors make less valuable (canned) products or put harvesters on limits during the peak of the run in abundant years, allowing the additional fish to escape. Compared with the BEGs, the proposed SEGs make a marginal change in the escapement goals that better balance years of limited fishing and exploitability of larger runs, leading to an increase in total catch and processor revenue of about 1% above the status quo SEGs.

These bay-wide results aggregate across outcomes for individual fishing districts, but district-level outcomes are important because not all fishermen can move among districts. Since different river systems have different run variabilities, some may experience more frequent years with few or no openings to meet higher escapement goals, leading to imbalanced or unacceptable distributional impacts among different components of the harvesting sector. To analyze district-specific effects, we show the number of days each east side commercial fishing district is open to fishing between 20 June to 17 July of each simulated year, the time frame in which most of fishing activity occurs. The east side stocks include Kvichak, Alagnak, Naknek, Egegik, and Ugashik. (See Fig. A1 for other stocks.)

Figure 4 shows the cumulative distribution of the number of simulated years across which a given district is open to fishing for the number of days on the *X* axis in the steady-state period of our forward simulations, taking the mean across iterations. The current SEG policy, the furthest line to the right in all panels, provides the most fishing opportunity in all districts. The slightly higher escapement goals of the proposed SEGs follow a similar pattern, whereas the BEG scenario is well to the left of the other two scenarios. This reflects that the individual districts are likely to have fewer fishing opportunities under BEG management, relative to the other two scenarios. For example, Ugashik is predicted to have zero fishing openings once in every five seasons, whereas under the other two escapement goal policies, Ugashik is com-

Table 6. Summary statistics from forward simulations.

(*a*) Returns and catch (in numbers) and revenues (2013 US dollars).

	Current SEGs	Proposed SEGs	BEGs
Annual return (all units in millions of fish)			
Median	36.93	41.03	50.25
Mean	40.43	44.49	54.17
Interannual variance*	413.74	489.95	681.13
Annual catch (all units in millions of fish)			
Median	23.00	24.18	22.85
Mean	23.81	24.93	23.94
Interannual variance*	54.99	61.70	79.99
Processor wholesale revenues (all units in millions 2013 US dollars)			
Median	329.37	343.14	328.48
Mean	334.19	347.23	335.41
Interannual variance*	6 957.09	7 689.94	10 079.54
Vessel revenues (all units in millions 2013 US dollars)			
Median	155.08	162.93	153.30
Mean	158.60	165.83	158.04
Interannual variance*	2 459.20	2 721.27	3 582.63

(*b*) Percent change between current SEGs and other escapement policies.

	Current SEGs	Proposed SEGs	BEGs
Annual return (all units in millions of fish)			
% change in median	—	9.71	33.88
% change in mean	—	10.86	37.87
% change in interannual variance*	—	23.73	108.28
Annual catch (all units in millions of fish)			
% change in median	—	4.77	0.23
% change in mean	—	5.13	1.47
% change in interannual variance*	—	13.56	49.98
Processor wholesale revenues (all units in millions 2013 dollar)			
% change in median	—	3.92	0.54
% change in mean	—	4.16	0.92
% change in interannual variance*	—	11.42	48.31
Vessel revenues (all units in millions 2013 dollars)			
% change in median	—	4.67	–0.20
% change in mean	—	5.11	0.54
% change in interannual variance*	—	11.64	49.60

*The interannual variance is based the mean of interannual variance within each iteration, averaged across iterations.

pletely closed only once every 20 years. Similarly, Egegik will offer no fishing opportunities once every 6–7 years under BEGs, but will offer at least some fishing 199 out of 200 years under either current or proposed SEGs. The rates of closure under the current and proposed SEGs are similar because openings are influenced not only by these stocks, but also by other (more abundant) east side stocks that swim through these districts. These closure rates are consistent with a recent 20-year period (1995–2015) when the annual returns were less than the lower range of the BEG twice in Ugashik and once in Egegik.

However, fewer opening days per season may not translate into lower ex-vessel revenues, if daily catches are larger. Figure 5 shows the distribution of ex-vessel revenue estimates for the Naknek–Kvichak, Egegik, and Ugashik districts. For the Egegik and Ugashik districts, BEGs lead to lower average ex-vessel revenues and a considerably higher chance of years with zero revenue than the other two scenarios, which are comparable in all districts (see also Fig. A2).

Both district closure frequencies and district-specific ex-vessel revenues suggest that even if higher escapement goals would lead to higher mean annual catch, the set-net sector and less mobile vessels may not necessarily benefit. Although the number of days open in each district decreases when the escapement goals are raised, the bay-wide total annual catches still increase. This implies that the independent stochasticity (variability) in returns across different river systems insulates mobile harvesters against closures in any particular district. Even if one district is closed for fishing due to lack of returns for the season, other districts can experience higher average returns supported by higher escapement goals, so the total catch can still be higher.

The decrease in district-specific openings under some escapement goal policies may also increase the proportion of years where little or no harvest opportunities are provided. We examine the probability of having total bay-wide catch of fewer than 5, 10, and 15 million fish under each scenario (Table 7). Based on our simulation results, low harvests are more likely to occur under BEGs than the other two scenarios. Catches below 10 million fish occur once in every 23 years under BEGs, but only once every 60 years under either proposed or current SEGs. In addition, harvests below 15 million fish occurred 18.1% of the time under BEG management, almost twice as often as under the other policy scenarios. Between the two SEG policies, the current SEG yields a slightly higher probability of low-harvest seasons than the proposed SEG. This is consistent with our earlier results in which the current SEG yields slightly lower average catch than the proposed SEG. This also suggests that a slight increase in interannual variance under the proposed SEG relative to the current SEG does not seem to impact overall catchability.

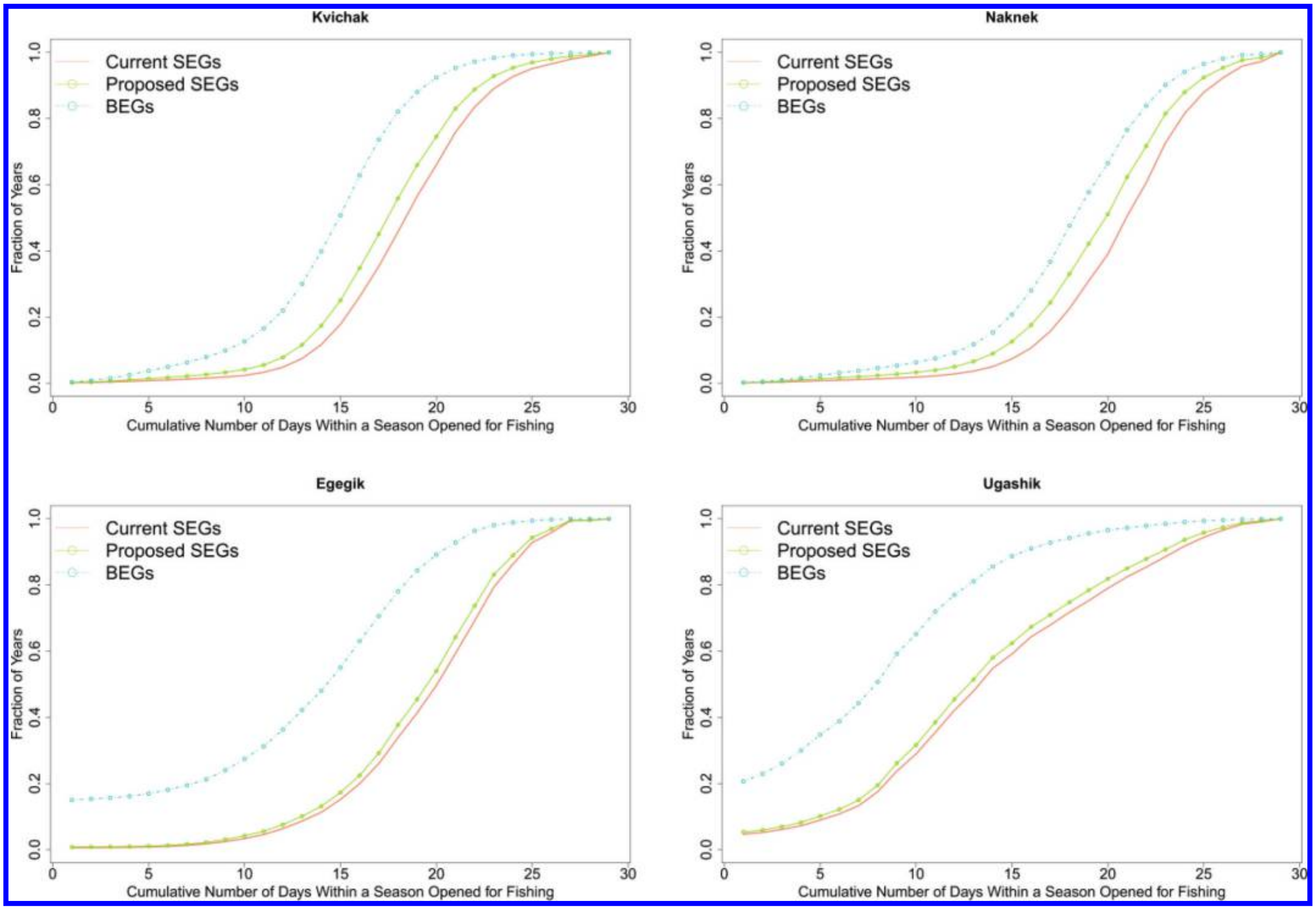
Discussion

We develop an economically sophisticated MSE incorporating processing decisions and product pricing into an assessment of steady-state outcomes under three escapement goal policies: the current SEGs, proposed SEGs, and the BEGs based on Fair et al.'s (2012) estimate of MSY. We find that incorporating processor and market response shifts the nature of the advice given to managers (ADF&G) and the Alaska Board of Fisheries, as more fish does not result in more money. Although average annual returns are considerably higher under the biologically motivated BEGs, average annual catches and processor wholesale revenues are comparable, and interannual variation is much higher.

This result illustrates one fallacy in the notion that fishery management policies that achieve MSY also support better economic and social outcomes for the fishery. Higher average fish returns under BEGs, relative to the other two scenarios, does increase (maximize) average potential sustainable yield, but behavioral responses to the associated variance mean that little of that potential yield is realized. In fact, our analysis predicts the MSY-based BEGs yield the lowest annual catch, despite BEGs' intended purpose. While daily landings can overwhelm daily markets or processing capacity leading to severe prices drops (e.g., Scheld et al. 2012), in those cases, value was increased by adopting management that incentivized smaller daily landings over a longer period. Our model shows that run variability, compressed natural season length, and limited processing capacity interact to create a situation — the only one of which we are aware — where economic benefits are increased by reducing biomass below B_{MSY}.

The mean–variance trade-off in Bristol Bay led Steiner et al. (2011) to suggest a constant harvest strategy, an idea whose most appealing feature is ignored in a typical MSY analysis (e.g., Bue et al. 2008): stable harvests are crucial to the stability of income to the harvesting and the processing sectors. This is particularly true for harvesters who specialize in one district in Bristol Bay, as an increase in their district's escapement goal(s) would lead to higher district-specific closure rates. Even if the average bay-wide catch is higher under higher escapement goals, including the proposed SEGs, the benefits will not be distributed equally across all harvesters. Set-net harvesters and less mobile driftnet harvesters might be worse off on average and could be more vulnerable when their district experiences more frequent low-catch, low-income years. Understanding this effect requires understanding

Fig. 4. Cumulative densities of number of days each district is open to fishing between 20 June and 17 July. [Colour online.]



human reactions to changes in fish abundance, here implemented with the daily management model and daily processing capacity.

To further extend the joint biological–economic sophistication of an MSE, additional economic approaches could be integrated. First, our steady state analysis is intended to facilitate long-run comparisons, but identifying the economically best policy would involve a cost–benefit analysis. This would calculate net present values, incorporating potential losses incurred during the transitional period as stocks build based on increased escapement goals, as well as the costs incurred due to any commensurate increases in processing capacity. Second, we generate future wholesale prices based on recent global market conditions, but these may change over time in foreseeable ways. For example, if continued competition from aquaculture puts pressure on wild sockeye prices, we may have further overestimated the potential value in increases in escapement goals and average run sizes. Incorporating a sensitivity analysis for pricing and processing technology parameters could indicate the robustness of our conclusions to possible future states of salmon markets.

To simulate the biological and management components of the Bristol Bay commercial sockeye salmon fishery, we made several assumptions by necessity, which may be worthy of evaluating in subsequent research. In simulating the management process, we made two specific assumptions about the data streams used to guide daily fishing effort decisions. First, escapement of sockeye on to the spawning grounds was assumed to be observed without error. Escapement to each river system is enumerated using visual counts, occurring for 10 min on each bank of the river from an elevated tower during each hour of the day, or using bank-associated sonar in the case of the Nushagak River. Given the clear water in most rivers, high nighttime levels of ambient light at this latitude in the summer, and placement of counting towers, these escapement estimates are generally assumed to have low bias and high precision. However, the observation error variance for escapement enumeration scales with the mean and may lead to greater implementation error during periods of high escapement. Second, the decision rules used to approximate in-season management behavior did not account for auxiliary information about salmon arrivals in addition to daily tower counts. These auxiliary data include aerial surveys of fish in the river between the fishing district and counting tower and daily catch per unit effort from the Port Moller Test Fishery, which intercepts salmon during the homeward migration and is operated by the Bristol Bay Science and Research Institute (Flynn and Hilborn 2004). While these auxiliary data streams may influence the in-season manager's decision process, it is unclear to what extent, and by necessity this information was not included. With respect to the simulation of Bristol Bay sockeye salmon biology, we assumed that both age and size at maturation were time-invariant; however, there is some suggestion that mass-at-age is density-dependent, having a negative correlation with return abundance, and that size at return exhibits an even–odd year pattern. While worth further exploration, ignoring these specific elements in our simulation of biological dynamics and the management process is unlikely to influence our overall results.

This case study also highlights important gaps in data that limit the nature and quality of economic outcomes that can be derived from the MSE model; this stands in stark contrast with the extensive biological data available in this fishery. Price and product form observations are limited to single annual values; data collec-

Fig. 5. Distributions of ex-vessel revenues, illustrated by violin density plots. The horizontal black line indicates the median value, and the white box represents the inner quartile range. The daily catch results were constructed using harvest rate by stock, rather than harvest rate by district. The stock-based structure of the biological model makes it infeasible to precisely establish ex-vessel revenues for the east side districts due to cross-stock catch. For example, when the Ugashik district is opened, catch is composed of not only the Ugashik stock, but also Naknek, Kvichak, and Egegik fish passing through Ugashik district on their way to their spawning rivers. These graphs are meant to be illustrative of the distributional considerations associated with limited openings in individual systems.

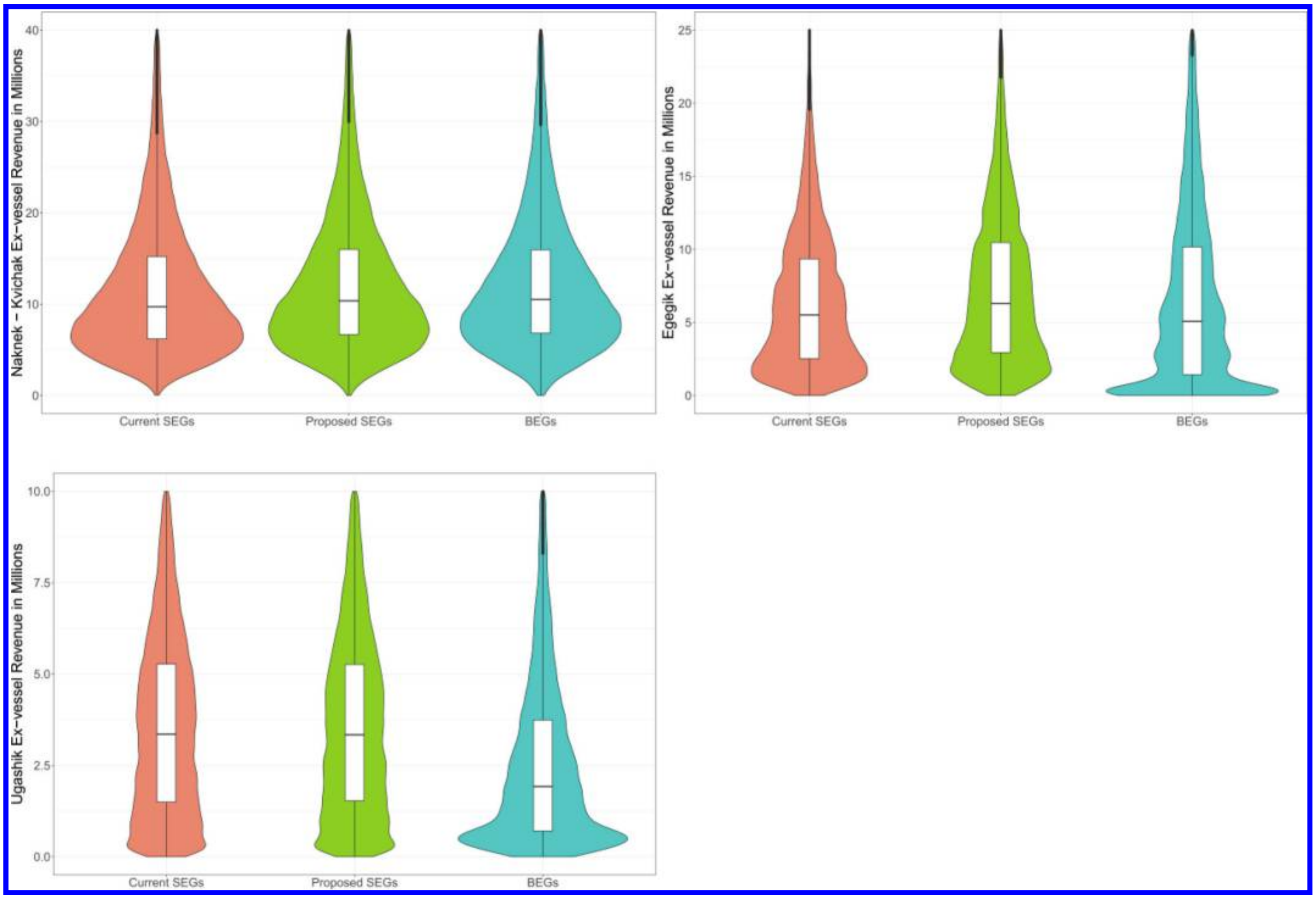


Table 7. Percentage of years when catches were less than 5, 10, and 15 million fish, bay-wide, across three escapement goal policies.

Catches less than:	Current BEGs	Proposed BEGs	BEGs
5 million fish	0.02%	0.03%	0.31%
10 million fish	1.94%	1.68%	4.43%
15 million fish	12.97%	10.76%	17.65%

tion practices and confidentiality obscure plant-level variation that could provide insight into how product form and pricing decisions interact. Further, new products like fillets have very short time series, and most of the publicly available data sources do not distinguish the production of sockeye frozen fillets and H&G, limiting our ability to understand substitution between these on both the production and wholesale sides. The processor model could also be better supported with annual surveys of number of days-on-limits and bay-wide processing capacity per line.

While this analysis focuses primarily on the behavioral response of the processing sector, economically sophisticated MSEs will broadly consider behavioral changes and distributional consequences arising from different management strategies. We did not explicitly incorporate harvest sector behavior because Olympic derby management has ensured sufficient harvest capacity was present in each day and each district, within the range of the data. During unusually abundant years, it is possible (though we think unlikely) that harvesting power is more limiting than the processing capabilities. However, future changes in management that affect participation, fleet capacity, or the ability to move among districts may affect outcomes. In particular, the MSE should consider the following: Who fishes? When? With what gear? Whether there will be environmental effects of that fishing behavior? And what effect will their behavior have on fishing costs? The latter are a key element of a complete welfare analysis.

In designing MSEs, analysts must identify and incorporate the primary sources of variation and uncertainty that might influence management procedures' attainment of objectives. Certain economic responses, such as inelastic market demand that lead to dramatic price decreases as quantity increases (this is uncommon), or highly costly behavioral changes that limit the fleet's exploitation of abundant stocks, are commonly considered ways that more fish may not lead to more money. This case study highlights the importance of considering behavioral responses to, and distributional consequences of, variability in abundance. Even with healthy stocks, harvesting and processing businesses are sensitive to variability in catches, and if variance is too high, they may fail to capture value from more abundant fish; indeed, they may be better off with a management strategy that provides for more consistent catches. Consistent catch management strategies will be favored in fisheries where daily processing capacity is exceeded in abundant years or spikes in catch lead to the erosion of product value (cf. Homans and Wilen 2005). Further, even if total revenue increases under a management strategy, stabilizing catch may minimize downside risk, the risk of catches so low that some participants become vulnerable to bankruptcy or are put in a position where they need to sell their fishing assets to deal with personal financial shocks. Thus, when fisheries are highly variable year to year, or when there is substantial heterogeneity in where in the structure of the resource stakeholders access it, understanding the consequences of alternative management plans indicates integrating models of the harvest and postharvest sectors.

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References

Asche, F. 1997. Dynamic adjustment in demand equations. Mar. Resour. Econ. **12**: 221–237. doi:10.1086/mre.12.3.42629197.

Asche, F., and Wessells, C.R. 2002. Demand equations with some nonstationary variables: the demand for farmed and wild salmon in Japan. Working paper No. 29/02. Centre for Fisheries Economics, Discussion paper No. 7/2002.

Asche, F., Bjørndal, T., and Salvanes, K.G. 1998. The demand for salmon in the European Union: the importance of product form and origin. Can. J. Agric. Econ. **46**(1): 69–81. doi:10.1111/j.1744-7976.1998.tb00082.x.

Baker, T.T., Fair, L.F., West, F.W., Buck, G.B., Zhang, X., Fleischman, S., and Erickson, J. 2009. Fishery Manuscript Series No. 09-05. Review of Salmon Escapement Goals in Bristol Bay, Alaska, 2009. Alaska Department of Fish and Game, Fishery Manuscript Series No. 06-05, Anchorage, Alaska, USA.

Bue, B.G., Hilborn, R., and Link, M.R. 2008. Optimal harvesting considering biological and economic objectives. Can. J. Fish. Aquat. Sci. **65**(4): 691–700. doi:10.1139/f08-009.

Cunningham, C.J., Schindler, D.E., and Hilborn, R. 2015*a*. An evaluation of biological escapement goals for sockeye salmon of Bristol Bay, Alaska [online]. University of Washington. Available from https://www.bbsri.org/escapement-goal-analysis.

Cunningham, C.J., Wang, J., Hilborn, R., Anderson, C., and Link, M.R. 2015*b*. Analysis of escapement goals for Bristol Bay sockeye salmon taking into account biological and economic factors [online]. University of Washington, School of Aquatic and Fisheries Sciences and LGL Alaska Research Associates, Inc. Available from https://www.bbsri.org/escapement-goal-analysis.

Cunningham, C.J., Branch, T.A., Dann, T.H., Smith, M., Seeb, J.E., Seeb, L.W., and Hilborn, R. 2018. A general model for salmon run reconstruction that accounts for interception and differences in availability to harvest. Can. J. Fish. Aquat. Sci. **75**(3): 439–451. doi:10.1139/cjfas-2016-0360.

Fair, L.F., Brazil, C.E., Zhang, X., Clark, R., and Erickson, J.W. 2012. Review of salmon escapement goals in Bristol Bay, Alaska, 2012. Alaska Department of Fish and Game, Fishery Manuscript Series No. 12-04, Anchorage, Alaska, USA.

Flynn, L., and Hilborn, R. 2004. Test fishery indices for sockeye salmon (*Oncorhynchus nerka*) as affected by age composition and environmental variables. Can. J. Fish. Aquat. Sci. **61**(1): 80–92. doi:10.1139/f03-142.

Gho, M. 2015. CFEC permit holdings and estimates of gross earnings in the Bristol Bay Commercial Salmon Fisheries, 1975–2014. Commercial Fisheries Entry Commission 15-4N, Juneau, Alaska, USA.

Hilborn, R. 2006. Mote Symposium Invited Paper Fisheries Success and Failure: the Case of the Bristol Bay Salmon Fishery. Bull. Mar. Sci. **78**: 487–498.

Homans, F.R., and Wilen, J.E. 2005. Markets and rent dissipation in regulated open access fisheries. J. Environ. Econ. Manage. **49**(2): 381–404. doi:10.1016/j.jeem.2003.12.008.

Knapp, G. 2004. Projections of future Bristol Bay salmon prices. Commercial Fisheries Entry Commission.

Knapp, G. 2013. Trends in Alaska and world salmon markets [online]. Available from http://www.iser.uaa.alaska.edu/people/knapp/personal/.

Knapp, G., Roheim, C.A., and Anderson, J.L. 2007. The great salmon run: competition between wild and farmed salmon [online]. Available from http://www.iser.uaa.alaska.edu/people/knapp/personal/pubs/TRAFFIC/The_Great_Salmon_Run.pdf [accessed August 2017].

Knapp, G., Guetttabi, M., and Goldsmith, S. 2013. The economic importance of the Bristol Bay salmon industry [online]. Available from http://www.iser.uaa.alaska.edu/Publications/2013_04-TheEconomicImportanceOfTheBristolBaySalmonIndustry.pdf [accessed August 2017].

Levi, T., Darimont, C.T., Macduffee, M., Mangel, M., Paquet, P., and Wilmers, C.C. 2012. Using grizzly bears to assess harvest–ecosystem tradeoffs in salmon fisheries. PLoS Biol. **10**: e1001303. doi:10.1371/journal.pbio.1001303.

Link, M.R., Hartley, M.L., Miller, S.A., Waldrop, B., Wilen, J., and Barnett, A. 2003. An analysis of options to restructure the Bristol Bay salmon fishery [online]. Bristol Bay Economic Development Corporation and Joint Legislative Salmon Industry Task Force. Available from http://www.bbsalmon.com/FinalReport.pdf.

Punt, A., Butterworth, D., de Moor, C., De Oliveira, J., and Haddon, M. 2016. Management strategy evaluation: best practices. Fish Fish. **17**: 303–334. doi:10.1111/faf.12104.

Scheld, A., Anderson, C., and Uchida, H. 2012. The economic effects of catch share management: the Rhode Island Fluke Sector Pilot Program. Mar. Resour. Econ. **27**(3): 203–228. doi:10.5950/0738-1360-27.3.203.

Schelle, K., Iverson, K., Free-Sloan, N., and Carlson, S. 2004. Bristol Bay salmon drift gillnet fishery optimum number report. Alaska Commercial Fisheries Entry Commission, Juneau, Alaska, Rep. (04-3N).

Steiner, E.M., Criddle, K.R., and Adkison, M.D. 2011. Balancing biological sustainability with the economic needs of Alaska's sockeye salmon fisheries. N. Am. J. Fish. Manage. **31**: 431–444. doi:10.1080/02755947.2011.588917.

Williams, A., Herrmann, M., and Criddle, K.R. 2009. The effects of Chilean coho salmon and rainbow trout aquaculture on markets for Alaskan sockeye salmon. N. Am. J. Fish. Manage. **29**: 1777–1796. doi:10.1577/M08-102.1.

Appendix A. Data sources

1. Alaska Salmon Program Bristol Bay Preseason Forecast (UW-FRI).

   Alaska Salmon Program publishes Bristol Bay preseason forecast every November. We use 2001–2012 preseason forecast data and the data set can be found at http://depts.washington.edu/aksalmon/.

2. Alaska Department of Fish and Game (ADF&G) COAR data.

   ADF&G COAR data are available upon request from the Alaska Department of Fish and Game. For this project, we use annual ADF&G COAR data for statewide and Bristol Bay sockeye salmon production from 1980 to 2010.

3. Alaska Department of Fish and Game (ADF&G) Commercial Salmon Harvests and Ex-vessel values.

Table A1. Mean age composition proportions used to allocate recruitment across age classes.

	Age class			
Stock	1.2	1.3	2.2	2.3
Igushik	0.23	0.67	0.06	0.04
Wood	0.46	0.47	0.05	0.03
Nushagak	0.1	0.82	0.04	0.03
Kvichak	0.24	0.1	0.59	0.07
Alagnak	0.29	0.53	0.1	0.09
Naknek	0.18	0.44	0.18	0.19
Egegik	0.08	0.15	0.45	0.32
Ugashik	0.28	0.31	0.28	0.13

Note: Age class *c.d* denotes a fish that spent *c* years in fresh water before spending *d* years at sea before returning to spawn.

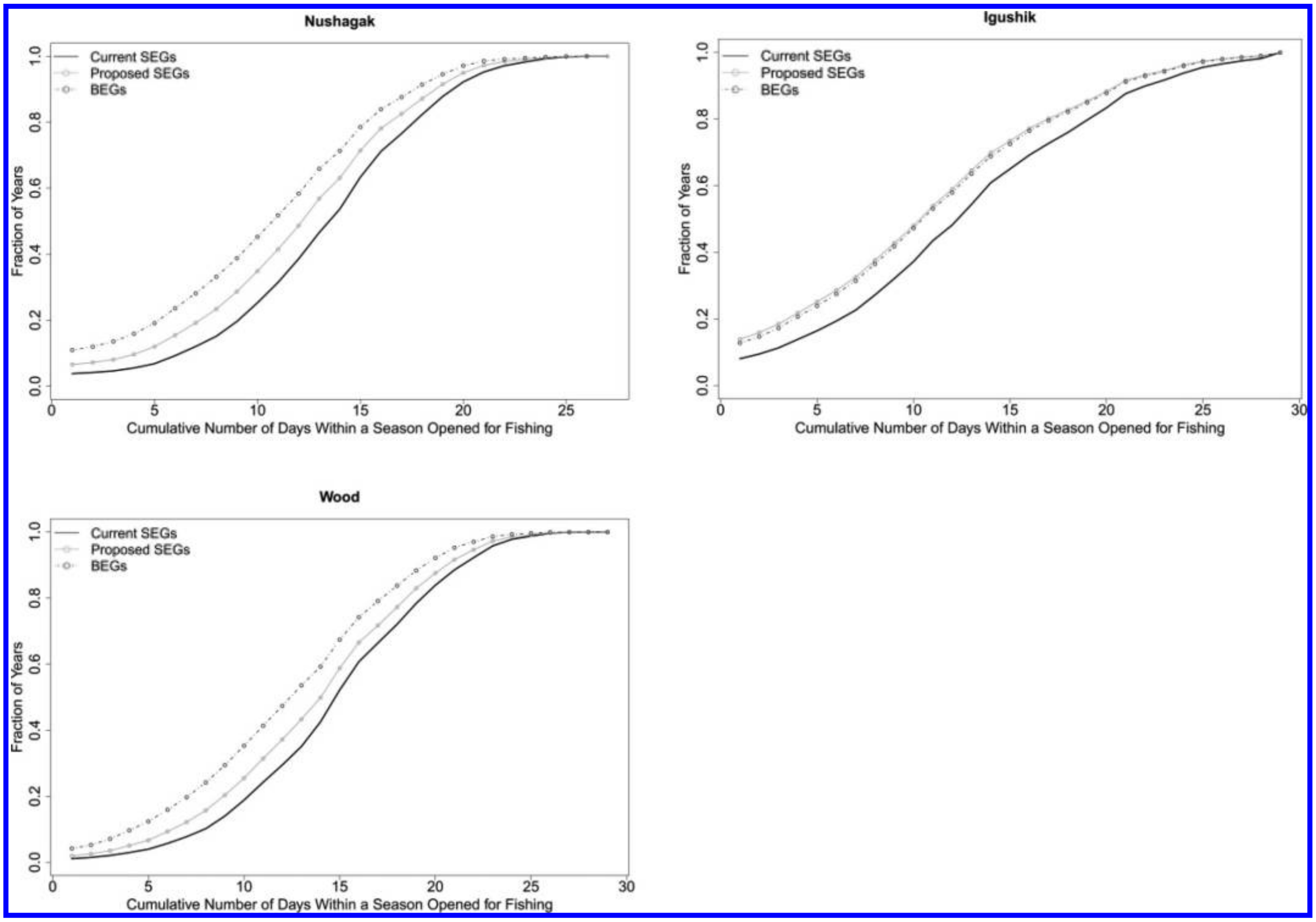
Table A2. Matrix of harvest rate by fishery option and population ($h_{f,p}$) for the west side of Bristol Bay.

Fishery option	Igushik	Wood	Nushagak
Nushagak section AND Igushik section	44%	60%	80%
Nushagak section ONLY	20%	60%	80%
Igushik section ONLY	30%	0%	0%
Wood River special harvest area	0%	80%	0%
None	0%	0%	0%
Wood River special harvest area AND Igushik section	30%	80%	0%

Table A3. Matrix of harvest rate by fishery option and population ($h_{f,p}$) for the east side of Bristol Bay.

Fishery option	Kvichak	Alagnak	Naknek	Egegik	Ugashik
None	0%	0%	0%	0%	0%
Naknek–Kvichak district ONLY	50%	45%	50%	5.2%	2%
Egegik district ONLY	5.1%	3.7%	6.5%	95%	10.1%
Ugashik district ONLY	0.6%	0.6%	0.4%	3.4%	60%
Naknek–Kvichak AND Egegik districts	52.5%	47%	53.3%	95.3%	11.9%
Naknek–Kvichak AND Ugashik districts	50.3%	45.3%	50.2%	8.4%	60.8%
Egegik AND Ugashik districts	5.7%	4.3%	6.9%	95.2%	64%
Naknek–Kvichak, Egegik, AND Ugashik districts	52.9%	47.3%	53.4%	95.4%	64.8%
Naknek River special harvest area	0%	0%	90%	0%	0%

Fig. A1. Cumulative number of simulated years that a given subdistrict was opened for a specified number of days during the period 20 June to 17 July.



ADF&G annual commercial salmon harvests and ex-vessel values can be found in the website below. We use annual data of Bristol Bay ex-vessel prices from 1994 to 2013 in this paper: http://www.adfg.alaska.gov/index.cfm?adfg=CommercialByFisherySalmon.exvesselquery.

4. Alaska Department of Labor and Workforce Development (Research and Analysis Section).

Alaska Department of Labor and Workforce Development provides Alaska census data, local employment by industry sector, and wages workers receive. We use 2001–2012 annual local employment by industry sector in the analysis. The data can be found at http://laborstats.alaska.gov/.

5. Alaska Department of Revenue Tax Division (ATR) data.

ART trimester wholesale prices and quantity produced of fillet, H&G, and canned from 2002 to 2013 in Bristol Bay are used in this paper and can be obtained from the following website: http://tax.alaska.gov/programs/programs/reports/index.aspx?60624.

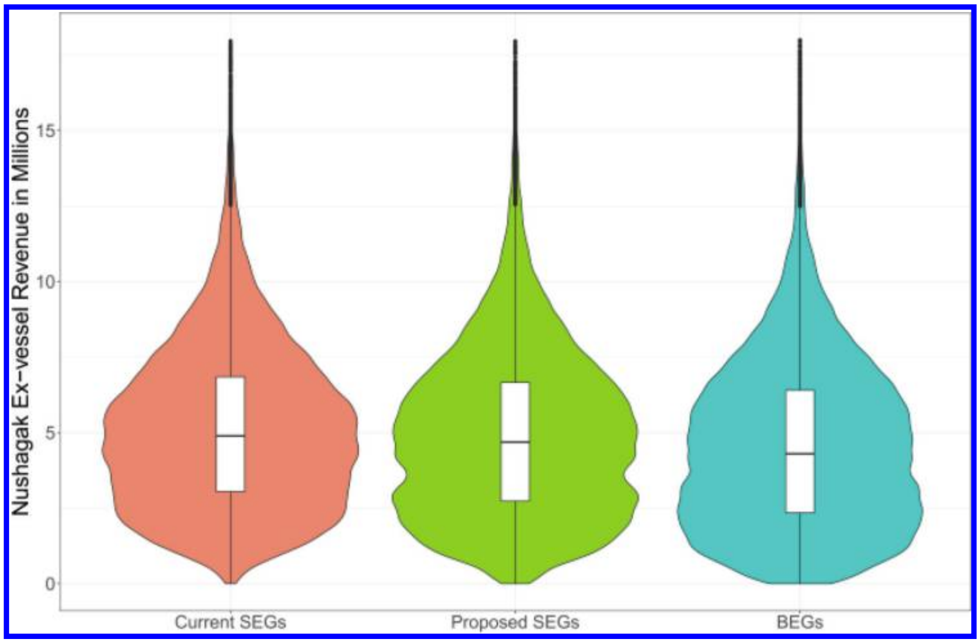
6. Department of Commerce, Community and Economic Development (DCCED) for State of Alaska.

Office of Fisheries Development under DCCED for State of Alaska publishes recovery rate and yields from pacific finfish and shellfish. The information can be found on the following website: https://www.commerce.alaska.gov/web/ded/DEV/FisheriesDevelopment/SeafoodProcessingRecoveryRatesYields.aspx.

7. Federal Reserve Bank of St. Louis Consumer Price Index (CPI) Data The Federal Reserve Bank of St. Louis posts monthly CPI. The data can be found at https://fred.stlouisfed.org/series/CPIAUCSL.

8. National Marine Fisheries Service (NMFS) Monthly Trade Data by Product, Country/Association.

Fig. A2. Distributions of ex-vessel revenues from the Nushgak district under three escapement goals policies across 100 simulations of final 74 years each.



NMFS reports detailed data on US imports, exports, and re-exports of salmon in the website below. We use monthly import and export quantities and prices from 1980 to 2012: https://www.st.nmfs.noaa.gov/commercial-fisheries/index.

References

Cunningham, C.J., Schindler, D.E., and Hilborn, R. 2015. An evaluation of biological escapement goals for sockeye salmon of Bristol Bay, Alaska. *Edited by* M.R. Link. University of Washington.

Cunningham, C.J., Branch, T.A., Dann, T.H., Smith, M., Seeb, J.E., Seeb, L.W., and Hilborn, R. 2018. A general model for salmon run reconstruction that accounts for interception and differences in availability to harvest. Can. J. Fish. Aquat. Sci. **75**(3): 439–451. doi:10.1139/cjfas-2016-0360.

Levi, T., Darimont, C.T., Macduffee, M., Mangel, M., Paquet, P., and Wilmers, C.C. 2012. Using grizzly bears to assess harvest-ecosystem tradeoffs in salmon fisheries. PLoS Biol. **10**: e1001303. doi:10.1371/journal.pbio.1001303. PMID: 22505845.

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