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RESEARCH ARTICLE

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Effects of increased specialization on revenue of Alaskan salmon fishers over four decades

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Abstract

1. Theory and previous studies have shown that commercial fishers with a diversified catch across multiple species may experience benefits such as increased revenue and reduced variability in revenue. However, fishers can only increase the species diversity of their catch if they own fishing permits that allow multiple species to be targeted, or if they own multiple single-species permits. Individuals holding a single permit can only increase catch diversity within the confines of their permit (e.g. by fishing longer or over a broader spatial area).
2. Using a large dataset of individual salmon fishers in Alaska, we build a Bayesian variance function regression model to understand how diversification impacts revenue and revenue variability, and how these effects have evolved since the 1970s.
3. Applying these models to six salmon fisheries that encompass a broad geographic range and a variety of harvesting methods and species, we find that the majority of these fisheries have experienced reduced catch diversity through time and increasing benefits of specialization on mean individual revenues.
4. One factor that has been hypothesized to reduce catch diversity in salmon fisheries is large-scale hatchery production. While our results suggest negative correlations between hatchery returns and catch diversity for some fisheries, we find little evidence for a change in variability of annual catches associated with increased hatchery production.
5. *Synthesis and applications*. Despite general trends towards more specialization among commercial fishers in Alaska, and more fishers exclusively targeting salmon, we find that catching fewer species can have positive effects on revenue. With increasing specialization, it is important to understand how individuals buffer against risk, as well as any barriers that prevent diversification. In addition to being affected

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by environmental variability, fishers are also affected by economic factors including demand and prices offered by processors. Life-history variation in the species targeted may also play a role. Individuals participating in Alaskan fisheries with high contributions of pink salmon — which have the shortest life cycles of all Pacific salmon — also have the highest variability in year-to-year revenue.

KEYWORDS
Alaska, Bayesian time-series modelling, catch diversity, commercial fishing, revenue variability, salmon, specialization

1 | INTRODUCTION

Commercial fishers experience high degrees of variability in revenue (Anderson et al., 2017; Sethi, Dalton, & Hilborn, 2012). Understanding the incentives and risks that fishers experience, as well as the diversification strategies they adopt to minimize year-to-year variability in revenue is important for maintaining sustainable livelihoods and productive fisheries. As in terrestrial agriculture (Purdy, Langemeier, & Featherstone, 1997), diversifying harvest may affect the mean or variance of revenue. Another parallel between fishers and farmers is that while the strategies of both may have some impact on revenue, a number of external drivers may also affect the ability or incentives to diversify. For commercial fishers, some of these factors include the prices offered by processors, the relative abundance of species and regulatory changes such as the adoption of permit or area restrictions. Because of the complexities of these factors, any benefits or costs of diversification may be variable through time.

Some of the most detailed analyses of relationships between catch diversification and revenue have been focused on Alaskan fisheries. Fisheries in Alaska are among the most productive in the world (Fissel et al., 2016) both by landed weight and revenue (Office of Science and Technology, 2016) and individual fishers adopt a broad range of strategies intended to enhance profitability. Previous analyses have investigated the effects of fishing strategies on communities (Cline, Schindler, & Hilborn, 2017; Himes-Cornell & Hoelting, 2015; Loring, 2016; Sethi, Reimer, & Knapp, 2014), vessels (Kasperski & Holland, 2013) and individual fishers (Anderson et al., 2017). One emergent pattern across these scales is that diversity may act as a stabilizing force against catch variability. However, there are many instances where specialization may be beneficial, to the extent that individuals may accept the risks of higher variability in revenue when it is accompanied by higher mean revenue (Anderson et al., 2017).

Anderson et al. (2017) defined fishing strategies by the permit or collection of permits held by single individuals. Some permits in Alaskan waters allow only one species to be targeted (e.g. sablefish, halibut, herring, crab, shellfish and sea cucumber), while other permits allow species groups to be targeted (e.g. groundfish, salmon). Individual fishers can diversify their catches by owning multispecies permits, or several single-species permits. Understanding the effects of catch diversification on revenue of salmon fishers is important because although overall participation in Alaskan fisheries has declined since the 1980s, many Alaskan salmon fisheries have seen increases in participation since 2000 (Figure SA1). Many of the individuals who participate in salmon fisheries are increasingly salmon specialists, in that they only hold a single permit (Anderson et al., 2017).

Five species of salmon are harvested in Alaska waters (Chinook [*Oncorhynchus tshawytscha*], chum [*Oncorhynchus keta*], pink [*Oncorhynchus gorbuscha*], sockeye [*Oncorhynchus nerka*] and coho [*Oncorhynchus kisutch*]), and individual salmon fishers can diversify their catch among the five species. However, fishing permits are available for combinations of gear types and regions within Alaska and in practice these fisheries show a range of species diversity (Figure SA2). Each of these permits is specific to a particular region, meaning that a permit holder is constrained by gear type and geography. Most salmon are caught with purse seines (six permit regions), drift gillnets (five) or set gillnets (12). While multiple salmon species are captured in some of these fisheries, there are also examples of fisheries where catch is dominated by a single species. Examples of specialized fisheries with low catch diversity include Bristol Bay set and drift gillnet fisheries that primarily harvest sockeye salmon. For these unique fisheries, specialization is associated with higher revenue and reduced variability in year-to-year revenue (Anderson et al., 2017). Mechanisms hypothesized to influence specialization or diversification in salmon fisheries have been reviewed by Knapp (2012). These include a number of exogenous drivers, such as competition from farmed salmon production, consolidation of salmon buyers, marketing, prices and new processing technology. Examples of periods with dynamic prices and abundance include periods of high salmon abundance and low prices (late 1980s—early 1990s), price declines in the early 2000s (ADFG, 2007), and subsequent increases in prices and catches (Figure 2; Figures SA3–SA5). Advances in processing technology, such as improved freezing technologies, may smooth prices across time because fish caught in 1 year may be sold the next (Knapp, 2012).

Perhaps one of the largest changes affecting catch diversity or incentives for Alaskan salmon fishermen to diversify has been an increase in the production of hatchery salmon. Because many management regulations (season openers, mesh size) have been designed to specifically target hatchery salmon returns, we expect hatchery programs to affect catch diversity. In addition to affecting encounter rates, increased hatchery production may influence prices or alter incentives to target particular species. The modern era of Alaska's large-scale hatchery programme began in the late 1970s in response to low returns (Stopha, 2016), with substantial increases in hatchery releases during the 1980s

(Leber, Kitada, Blankenship, & Svasand, 2008; Mahnken, Ruggerone, Waknitz, & Flagg, 1998; Ward, Adkison, et al., 2017). Many of these hatchery programs increased production in an effort to stabilize the variability in salmon catches (Brooks, 1976; Hilborn & Eggers, 2001), and while recent work has suggested these programmes may increase total yield (Amoroso, Tillotson, & Hilborn, 2017), quantitative support for reduction in revenue variability remains unclear. Previous work has largely concentrated on the ecological effects of hatcheries (Hilborn, 1992; Hilborn & Eggers, 2001; Ruggerone & Connors, 2015; Wertheimer, Smoker, Joyce, & Heard, 2001), or economic yield (Boyce, Herrmann, Bischak, & Greenberg, 1993; Leber et al., 2008). Understanding the role salmon have in buffering or stabilizing fishing revenues is critical given the responses of salmon to variable ocean environments (Mueter, Peterman, & Pyper, 2002; Schindler et al., 2010).

Here, we use a range of salmon fisheries in Alaska to examine the effect of catch diversification on revenue and revenue stability. We present summaries of the five main salmon gear types in each region across a wide range of salmon fisheries to understand the overall relationship among revenue, stability or variability in revenue, and diversity of catches. Focusing exclusively on salmon fisheries, we extend the dataset used by Anderson et al. (2017) to include 12 more years of data, 1975–2016. We also extend the time-series models of Anderson et al. (2017) to include time-varying effects of catch diversification, to compare temporal trends across regions and to identify periods when having a diverse catch portfolio was most beneficial. Finally, we focus on a subset of salmon fisheries affected by hatcheries, examining how variation in hatchery production influences catch stability.

2 | MATERIALS AND METHODS

2.1 | Data

We obtained fisheries landings and revenue data for all permit holders in Alaska from 1975 to 2016 from the Commercial Fisheries Entry Commission (CFEC). Reported gross earnings (revenue) associated with each fish ticket—a mandatory record provided by processors of the weight and species of the catch delivered at each landing—were adjusted for inflation by converting all revenues to 2009 USD (United States Bureau of Economic Analysis, 2017). Each fish ticket was associated with both a vessel and permit holder, and because of our focus on individuals, we aggregated data at the level of permit holders to generate annual summaries of catch diversity and revenue. Fisheries were defined as groups of individuals holding the same permit. While we use the entire CFEC dataset, subsets of data are useful to understand particular aspects of the relationship between revenue and diversity (e.g. fisheries with low species diversity, such as the Bristol Bay gillnet fisheries were not included in some models because individuals are highly specialized).

To identify shared and unique trends among salmon fisheries, summaries of revenue, revenue variability and species diversity were calculated for all of the major salmon fisheries over the 41-year time series. This includes information from permits in all of the five major gear types: purse seine, drift and set gillnets, hand troll, and power troll. In addition to calculating mean revenue, variability in revenue, and mean catch diversity for each fishery, we generated time series of each quantity to identify long-term trends.

2.2 | Evaluation of effects of diversification over time for individual salmon fishers

To understand how altering catch diversification affects individual revenue and revenue variability, we focused on two gillnet and four purse seine salmon fisheries where effective diversity of the catch is larger relative to other salmon fisheries (Table 1; Figures SA6 and SA7). The data-filtering steps described in Anderson et al. (2017) were applied to fish ticket data for years 1975–2016. We aggregated trip-level catch and revenue data to annual summaries for each individual permit holder. We restricted our analysis to only include permit holders who participated in a single fishery in a year; to avoid complications in modelling, pairs of years where individuals changed participation in fisheries from the first to the second year were not included. Effective catch diversity was used as a proxy for diversification, calculated as the inverse of Simpson's diversity (Anderson et al., 2017; Jost, 2006; Kasperski & Holland, 2013), with each species' contribution determined in terms of revenue, rather than landed weight. Effective catch diversity values near 1.0 indicate that an individual's revenue is dominated by a single species, whereas an effective catch diversity of 3.0 indicates that three species contribute equally to revenue. Following Anderson et al. (2017), we used a class of Bayesian regression models to simultaneously estimate the effects of catch diversification on an individuals' mean annual revenue and variability in annual revenue, accounting for variability between fisheries and individuals. The natural log of revenue for individual i in fishery j and year t is modelled as

$$\ln(R_{i,j,t}) = B_{0,j,t} + B_{1,j,t} \cdot \Delta S_{i,t} + B_{2,j,t} \cdot (\Delta S_{i,t} \cdot S_{i,t-1}) + B_{3,j} \cdot \Delta D_{i,t} + \ln(R_{i,t-1})$$

where j subscripts the salmon permit (Table 1). The variables $\Delta S_{i,t} = \ln(S_{i,t}/S_{i,t-1})$ represent the per cent change in species diversity of the catch and $\Delta D_{i,t} = \ln(D_{i,t}/D_{i,t-1})$ represents the per cent change in fishing effort (days fished) between years. Time-varying intercepts, specific to each permit (Table 1), were modelled as random and exchangeable across years, $B_{0,j,t} \sim \text{Normal}(u_{B_0}, \sigma_{B_0})$. The term $B_{1,j,t}$ represents the permit-level random effect of increasing catch diversity. We also included the terms $\Delta S_{i,t} \cdot S_{i,t-1}$, which forced the effect of diversification to be linear but allowed its strength to vary through time. The coefficients $B_{1,j,t}$ and $B_{2,j,t}$ were included to allow the interaction to vary by permit and year. The flexibility of this model allowed the benefit of a fisher increasing catch diversity to be positive in some years (generalizing translates to increased revenue), negative in other years (specializing increases revenue) and neutral in other years (revenue is independent of alterations to catch composition). We constrained the random effects associated with diversification to have shared variances across strategies (permits), for example: $B_{1,j,t} \sim \text{Normal}(0, \sigma_{B_1})$. The effect of changing effort (measured as per cent change in days fished) $B_{3,j}$ was allowed to vary by strategy, but we did not allow this effect to vary through time. Finally, the term $\ln(R_{i,t-1})$ was included as an offset because individual revenues are typically non-stationary.

TABLE 1 Salmon fisheries that were included in the analysis of catch diversification on revenue and revenue variability

Fishery	Gear	Region	Target species (2015)
S01A	Purse Seine	Southeast Alaska	Chum, pink
S01E	Purse Seine	Prince William Sound	Chum, pink
S01K	Purse Seine	Kodiak	Pink, sockeye
S01M	Purse Seine	Alaska Peninsula	Pink, sockeye
S03A	Gillnet	Southeast Alaska	Chum, sockeye
S03E	Gillnet	Prince William Sound	Sockeye, chum, Chinook

The second component of this regression model involved effects on the variability in annual revenue. Modelling the mean and variance simultaneously makes the model akin to variance function regression or stochastic volatility models (Anderson et al., 2017; Smyth, 1989; Western & Deidre, 2009). Our model for the standard deviation was

$$\ln(\sigma_{i,j,t}) = G_{0,j} + G_{1,j,t} \cdot \Delta S_{i,t} + G_{2,j,t} \cdot (\Delta S_{i,t} \cdot S_{i,t-1}) + G_{3,j} \cdot \Delta D_{i,t}.$$

We constrained the variance intercepts $G_{0,j}$ to be constant by permit. As in the mean model, the random effects were allowed to be independent by permit and year, $G_{1,j,t} \sim \text{Normal}(0,\sigma_{G_1})$, and covariates associated with days fished, $\Delta D_{i,t}$, and species diversity $\Delta S_{i,t}$ were included as predictors.

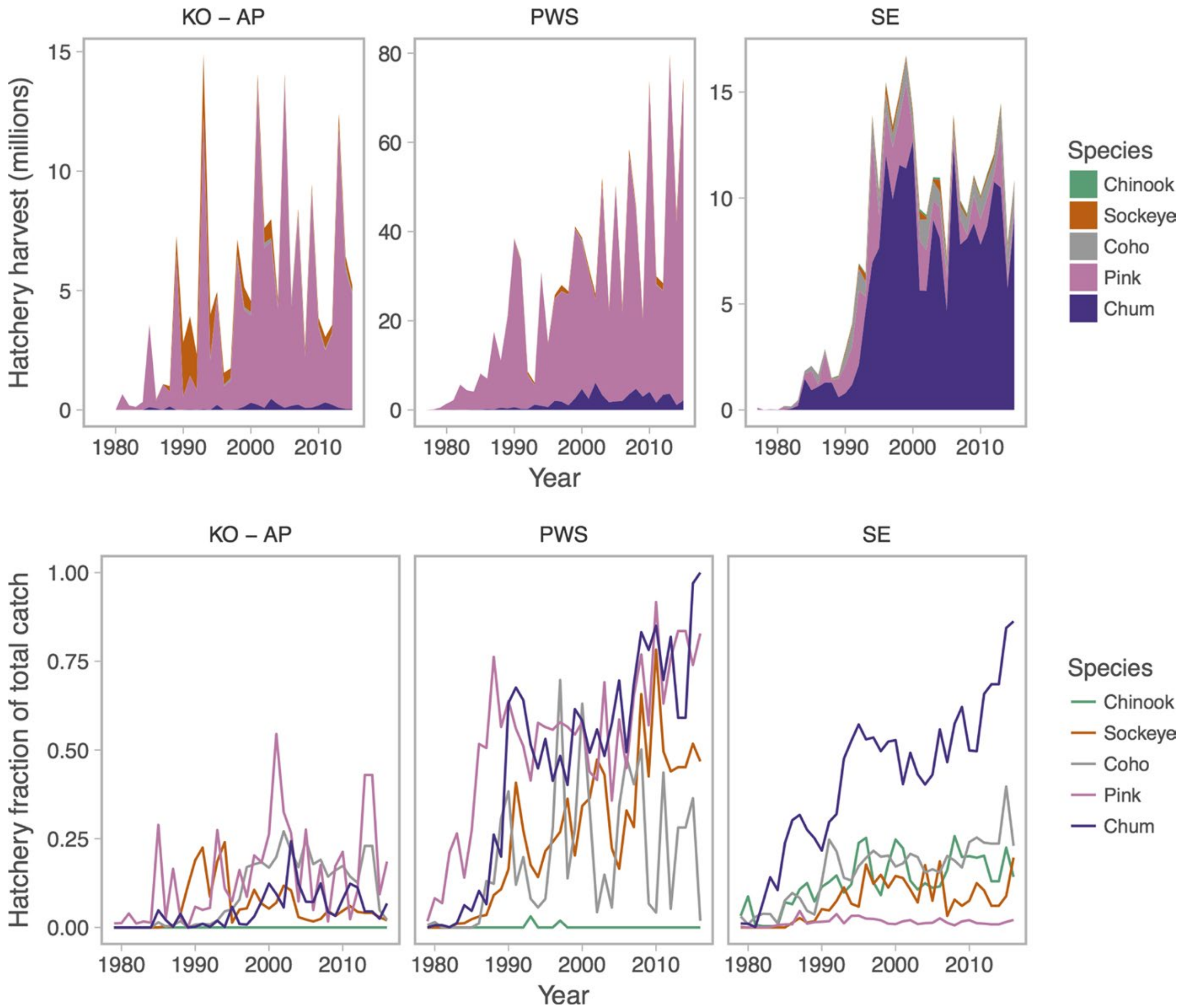

FIGURE 1 Harvest of hatchery-produced salmon through time by species and region. Shown are the numbers of hatchery fish caught by fisheries (top row), and the hatchery contribution of each species to total catch (bottom row). Regions represents combined Kodiak and Alaska Peninsula (KO–AP), Southeast (SE) and Prince William Sound (PWS)

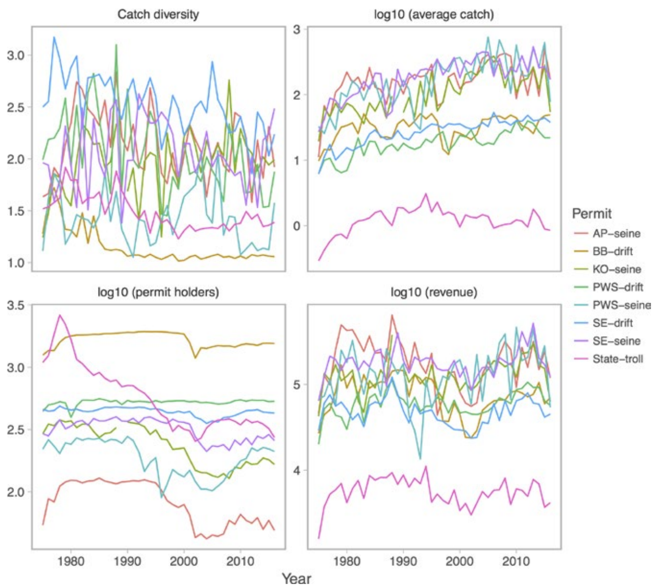

FIGURE 2 Trends in catch diversity, landed catch (metric tons), participation (permit holders) and mean annual revenue for eight selected Alaska salmon fisheries. The troll fishery permits (hand and power troll) do not have an associated area (statewide) but the majority of fishing is done in Southeast Alaska. Areas associated with permits include the Alaska Peninsula (AP), Bristol Bay (BB), Kodiak (KO), Prince William Sound (PWS) and Southeast Alaska (SE)

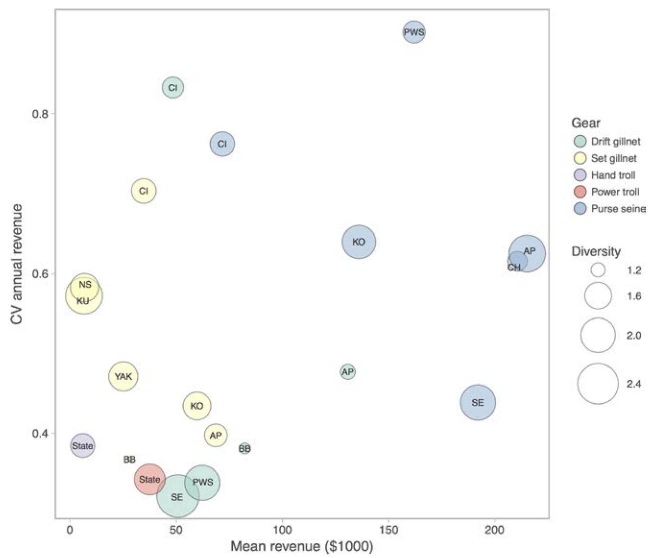

FIGURE 3 Coefficient of variation (CV) and mean annual revenue by salmon permit type, 1975–2016. Effective species diversity of catch (1/Simpson's diversity) is represented by circle area, fishing gear types are shown with colour shading. Labels indicate regions—Alaska Peninsula (AP), Bristol Bay (BB), Chignik (CH), Cook Inlet (CI), Kodiak (KO), Kuskokwim (KU), Norton Sound (NS), Prince William Sound (PWS), Southeast Alaska (SE), Yakutat (YAK). The troll fishery permit does not have an associated area (statewide), but the majority of fishing is done in Southeast Alaska

2.3 | Relationships between hatchery production, diversity and catches

To quantify potential effects of hatchery production on diversity and catch variability we used data from the seine and gillnet fisheries in Prince William Sound (PWS) and Southeast Alaska (SE) and assessed correlations in catch diversity (Figures SA6 and SA7) with returns of dominant hatchery species (Figure 1). In Southeast Alaska, we examined correlations in catch diversity with hatchery chum returns, because chum are caught by both seine and gillnet fisheries (Figures SA6 and SA7). For PWS, we calculated the correlations of catch diversity of the seine fishery with hatchery returns of pink salmon (Figure SA6) and the catch diversity of the gillnet fishery with hatchery returns of sockeye salmon (Figure SA7).

To quantify relationships between hatchery production and catch variability, we used the landed catch from each region and species as a response (following Amoroso et al., 2017; Hilborn & Eggers, 2001; Knapp, Roheim, & Anderson, 2007). Using a variance function regression model, we extended the approach of Amoroso et al. (2017) to model variability in salmon catches as a continuous function of the hatchery contribution of catches. Within each region (Table 1), the hatchery contribution to catches and total catches of each species are from Stopha (2016), with Kodiak and the Alaska Peninsula grouped because of reporting. The catch of each species in each region was modelled as,

$$E[Y_{s,f,t}] = Y_{s,f,t-1} + b_{s,f} X_{s,f,t}$$

where $Y_{s,f,t-1}$ is the catch of species s in region f in the previous time step $t-1$, $b_{s,f}$ is a coefficient relating the contribution of hatchery fish to the mean catch, and $X_{s,f,t}$ is the change in the proportion of hatchery contribution to the total catch for species s between times t and $t-1$. The hatchery-effect coefficients were modelled hierarchically, so $b_{s,f} \sim \text{Normal}(u_b, \sigma_b)$, where u_b and σ_b represent the mean and standard deviation of the random effects. Our second equation relates the change in proportion of hatchery contribution to the catch variability,

$$\ln(\sigma_{s,f,t}) = g_{0,s,f} + g_{1,s,f} X_{s,f,t}$$

where $g_{0,s,f}$ represents an intercept unique to each region and species, and $g_{1,s,f}$ represents a region- and species-specific slope, $g_{1,s,f} \sim \text{Normal}(u_g, \sigma_g)$. Combining the regression of the mean and variance, the observed catches were assumed to be normal $\ln(Y_{s,f,t}) \sim \text{Normal}(E[\ln(Y_{s,f,t})], \sigma_{s,f,t})$.

2.4 | Estimation

Estimation for both sets of models was in a Bayesian framework using R (R Core Team, 2017) and the package RSTAN (Stan Development Team, 2017), implementing Markov chain Monte Carlo (MCMC) using the No-U Turn Sampling (NUTS) algorithm (Carpenter et al., 2017; Hoffman & Gelman, 2014; Stan Development Team, 2015). We used three MCMC chains, with a warm-up period of 4,000 samples, followed by 5,000 saved iterations. Posterior estimates were visually examined for chain convergence with trace plots, and the potential scale reduction factor (Gelman & Rubin, 1992) was used as a tool to ensure convergence ($\hat{R} < 1.05$). Code to replicate our analysis, including

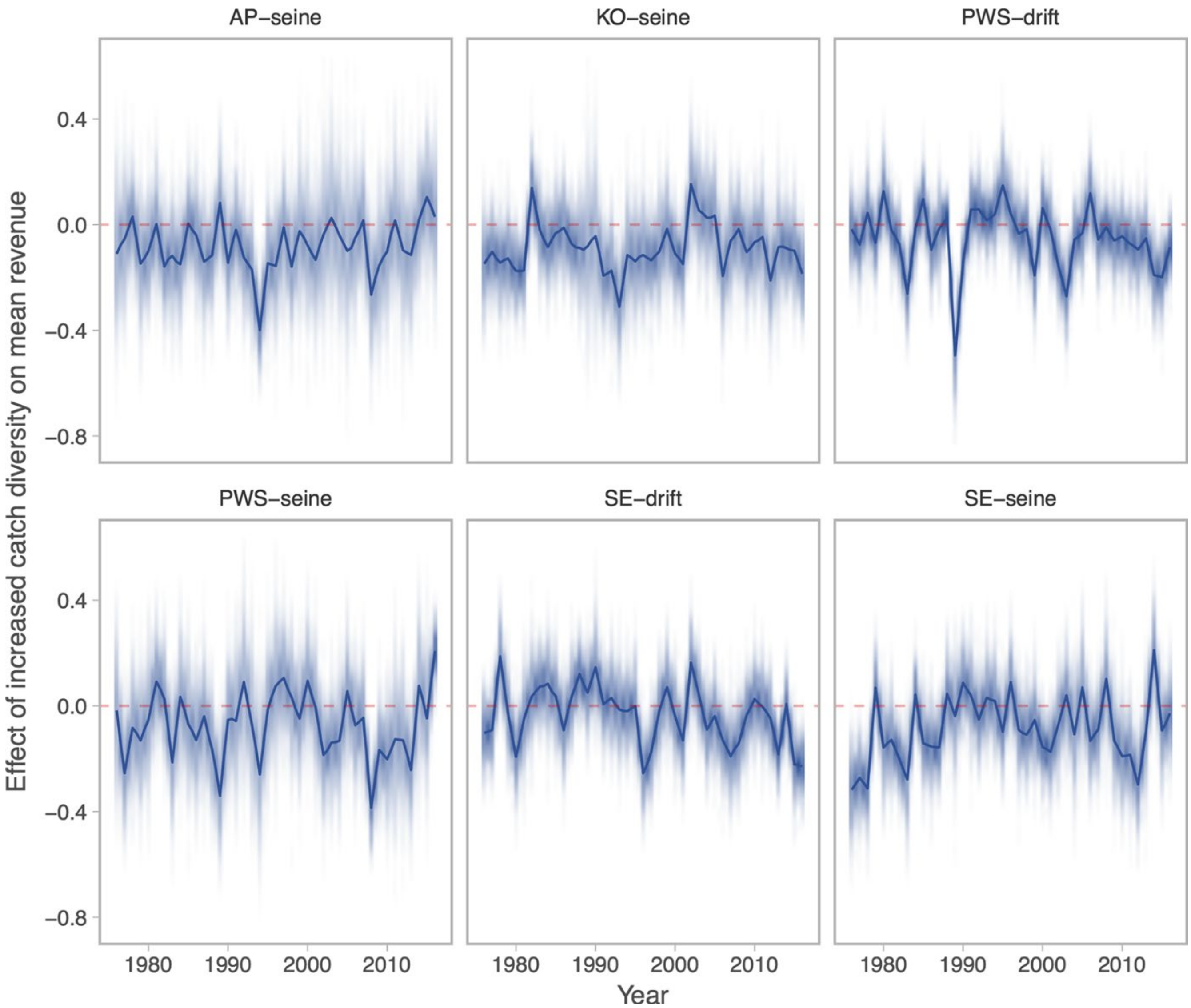

FIGURE 4 Time-varying effects of increasing the effective species diversity of catch (1/Simpson's diversity) from 1 to 2 species on mean revenue (presented as log ratios). The solid lines indicate the mean effect and 95% credible intervals are shown with shading proportional to density. Labels indicate regions and gear type—Alaska Peninsula (AP), Kodiak (KO), Prince William Sound (PWS), Southeast Alaska (SE) seine net or drift gill net

additional diagnostics plots, and additional models is available at https://github.com/NCEAS/pfx-commercial-salmon.

3 | RESULTS

Since the early 2000s, Alaskan salmon fisheries have generally experienced an increase in individual participants, landings have increased faster than revenue, and species diversity of landed catch has declined over time (Figure 2; Figures SA1, SA6 and SA7). Across salmon fisheries, there appears to be little correlation between catch diversity and revenue (Figure SA2), although fisheries cluster by gear type on axes of risk (CV of annual revenue) and return (mean annual revenue, Figure 3).

Most fishers participating in the six salmon fisheries in our analysis experienced changes in effective catch diversity that typically increase or decrease by one species per year (Figure SA8). Our model of individual revenues suggests that catch diversity in these six fisheries has declined over time (Figures SA6 and SA7). The estimated negative effects of increasing diversity on mean revenue (Figure 4) implies that for the majority of these fisheries in most years, revenue increases when individuals specialize and reduce the diversity of their catches. Across fisheries and years, the range of estimates (95% CIs) suggests that for an individual earning 100,000 dollars, diversifying from one to two species may reduce revenue to 68,000 dollars in years when specialization is favoured, or may increase revenue up to 130,000 dollars when diversification is favoured. The slight negative trends in these estimated effects for some fisheries in recent years (PWS and SE drift gillnet) suggest that the benefits of specializing have also increased over time (Figure 4). More importantly, our estimates suggest that individuals experience changing incentives

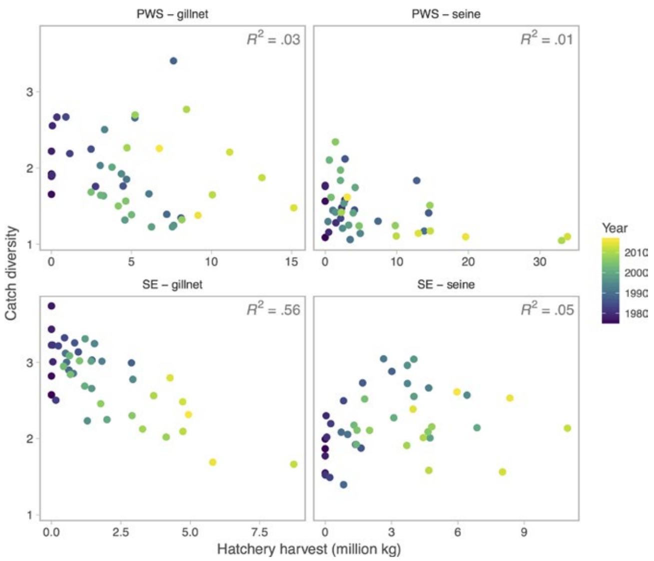

FIGURE 5 Catch diversity (1/Simpson's diversity) and harvest of dominant hatchery species by year. For Southeast Alaska gillnet and seine fisheries we used harvest of hatchery chum salmon, for the PWS gillnet fishery we used harvest of hatchery sockeye salmon, and for the PWS seine fishery we use harvest of hatchery pink salmon

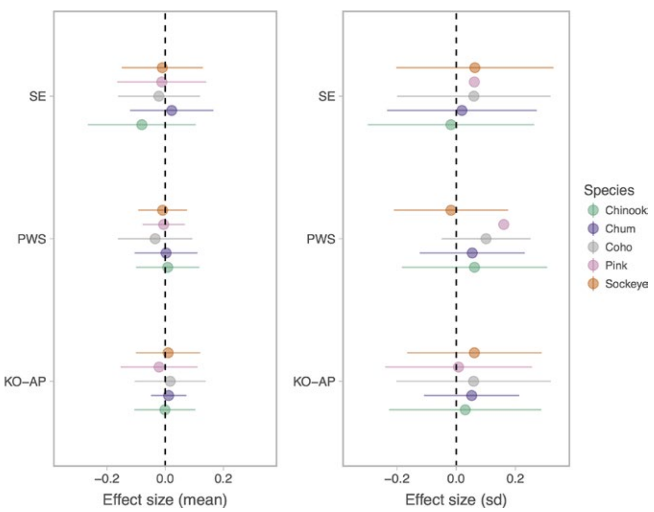

FIGURE 6 Effects of the fraction of hatchery fish on (1) mean annual catches, and (2) standard deviation of annual catches, for three areas (KO-AP = Kodiak and Alaska Peninsula, PWS = Prince William Sound, SE = Southeast). Effect sizes are presented as the percentage change from an increase from 0% to 20% hatchery fish. Dots represent mean estimates and error bars represent 95% CIs

to diversify over time. From 2008 to 2010, for example, it was not beneficial for individuals in the PWS or SE seine fisheries to diversify (negative effects in Figure 4), but several years later these trends reversed for seine fisheries, indicating a more diverse catch translated into higher revenue (Figure 4).

Our results also showed contrasts in year-to-year variability between seine and gillnet fisheries, with individuals in seine fisheries experiencing higher annual variability in revenue (Figure SA9). Across individual fishers, seine fishers are generally higher on both axes of risk and return (CV of annual revenue vs. mean annual revenue; Figure 3). Although the catch composition has fluctuated through time in areas where seine and gillnet fisheries exist (PWS, SE), catch diversity is slightly higher in gillnet fisheries (Figures SA6 and SA7). In most fisheries, we found little evidence that individuals who increased catch diversity reduced their revenue variability (Figure SA10). For several fisheries (SE seine and gillnet, PWS gillnet), there have been periods over the last several decades where diversification has increased variability, such as 2008–2010 (Figure SA10). For most other fisheries, these effects of diversifying are near zero (Figure SA10).

For the four fisheries in PWS and SE that are influenced by hatchery production, we found negative correlations between the share of the dominant hatchery species and total catch diversity in all but the SE seine fishery (Figure 5). These correlations were strongest for SE gillnet fisheries targeting chum salmon $\rho = -0.76$ ($p < .01$; Figure 5).

We found no consistent support for strong positive or negative relationships between variability of catches and the hatchery contribution to returns based on model results. To allow for comparison across regions and scales of data, we converted coefficient estimates to effect sizes, calculating the approximate per cent change in standard deviation resulting from the hatchery contribution increasing by 20%, $\kappa_s = \ln\left(\frac{g_{0,s}+0.2g_{1,s}}{g_{0,s}}\right)$. For the three regions in our analyses, most estimates of these effect sizes are near zero (Figure 6). The largest positive correlations between hatchery contribution and variability in catches appeared to be for coho and pink salmon in PWS (Figure 6), and a slight negative effect was found between the hatchery contributions and Chinook salmon catches in SE. The 95% credible intervals for these estimates overlap zero, however, and the estimated effect sizes are relatively small in magnitude.

4 | DISCUSSION

Determining the mechanisms responsible for trends or variability in the revenue of individuals whose incomes are dependent on natural resources is important for understanding the dynamics of coupled social-ecological systems. Income variability for such individuals is typically greater than that of the larger population (Mishra, El-Osta, Morehart, Johnson, & Hopkins, 2002; Sethi et al., 2012). Individuals participating in some commercial salmon fisheries in Alaska may have the option to increase the diversity of their catches. Diversification strategies may include buying additional permits, but many fishers have become single-permit holders (Anderson et al., 2017). For those individuals, targeting additional species allowed by the permit is the only option for diversifying catch. Our analysis illustrates that catch diversity has declined in some salmon fisheries. In recent years, catches from several of these fisheries have been dominated by a single species, namely sockeye salmon in the Prince William Sound gillnet fishery, pink salmon in the Prince William Sound seine fishery and chum salmon in the Southeast Alaska gillnet fishery (Figures SA6 and SA7).

As in other commercial fisheries, the ability of salmon fishers to diversify within the constraints of their permits may be largely driven by factors beyond their control. Our comparison among salmon gear types revealed that aspects of revenue and variability are determined in part by permit type (Figure 3). One mechanism responsible for these differences may include differences in species targeted—seine nets typically target pink or chum salmon, whereas gillnets typically target a more diverse species. A second mechanism is likely related to vessel and crew size. For example, smaller setnet and gillnet vessels (6–15 m) typically operate with crew of one to three people, while larger seine vessels (18 m) are operated by crews of four or more. The limited options of salmon fishers in Alaska to diversify may include fishing in different months or different regions. For example, individuals participating in the Prince William Sound seine fishery may fish earlier in the year to target chum salmon. External economic incentives for salmon fishers to specialize or diversify are complex, and include a suite of factors: competition from foreign markets, accessibility to buyers and prices from processors, fuel costs and marketing (e.g. increased marketing of Copper River sockeye salmon beginning in the early 1980s; Knapp, 2012). A potential driver unique to Alaska salmon fisheries is the effect of hatchery production. Increased hatchery production may alter the species composition that individual fishers encounter, particularly if fishing seasons are designed to intercept large hatchery runs. Since the early 2000s, for example, some of the largest increases in prices of all salmon were among pink and chum (Figures SA4 and SA5). In areas with high pink or chum salmon runs, the benefits of diversification may have been greatest when these species had low returns. For pink salmon returns with strong 2-year oscillations, for example, this would correspond to even- vs. odd-years.

Results from our regression model of individual fisher revenues over the period 1975–2016 suggest that there have been long-term increases in the benefits of individual fishers specializing (i.e. expected revenue increases when catch diversity decreases; Figure 5). For most of the time series, the impacts of changes to catch diversity on variability in year-to-year revenue are less clear. However, a counter-intuitive result is that since the mid-2000s, individuals participating in fisheries in Prince William Sound and seine fisheries in Southeast Alaska experienced an increase in revenue variability associated with increased diversification (Figure SA10). Some of this relationship may be spurious, in that individuals who reduce effort and catches because of unmodelled factors (e.g. illness, gear or vessel malfunctions) and this reduction in landings may be accompanied by a relative increase in species diversity (Figure SA11).

An additional potential effect of increased hatchery production may be changes in the variability of catches and/or revenues to fisheries or individuals. Across multiple regions in Alaska, we found little support for catches stabilizing as hatchery programmes have increased. However, one example of a positive correlation between the hatchery contribution to harvest variability is pink salmon in Prince William Sound (Figure 6). Our model describing the revenues of individual fishers also suggests that individuals in the Prince William Sound seine fishery have higher revenue variability relative to other fisheries (Figures 2 and 3, Figure SA9), with year-to-year revenue changes being correlated with fluctuations in pink salmon returns (Figure SA12). Pink salmon have the least variable life-history characteristics of all Pacific salmon, with a fixed 2-year life cycle and well-documented odd or even year dominance for a particular area (Quinn, 2005). The catch composition of the PWS seine fishery is heavily dominated by pink salmon and has a low level of species diversity (Figures 1, 2 and 4). Therefore, revenue variability for this fishery may be a function of the lack of catch of other species in the fishery and the life-history traits of pink salmon (which are mostly of hatchery origin). In contrast, the Southeast Alaska seine fishery has a low level of catch diversity but is dominated by wild pink salmon from *c*. 2,000 streams (Dangel & Jones, 1988) and large numbers of hatchery chum salmon, and may be buffered against fluctuations in revenue (Figures 2 and 3) by the portfolio of multiple populations (e.g. Schindler et al., 2010) and—for chum salmon—a more diverse suite of life-history characteristics.

The increased specialization of Alaska fisheries has been highlighted in several recent analyses (Anderson et al., 2017; Kasperski & Holland, 2013; Sethi et al., 2012), and our analysis extends this work to show similar trends within individual salmon permits. In terrestrial agriculture, there are multiple examples of year-to-year income variability being stabilized by diversification (Di Falco & Perrings, 2003), but these incentives become more complex at larger scales. Crop diversification in developed countries is shaped by a number of drivers including changing national policies, technology and increased demand from other parts of the world (e.g. US production of soybeans for Asian countries; Aguilar et al., 2015; Bradshaw, Dolan, & Smit, 2004). Shifts in terrestrial agriculture from a diverse mix of low- and high-value crops to focusing on high-volume low-value crops (such as soybeans or cereals) may have parallels for Alaskan salmon fisheries—particularly those fisheries that have more recently targeted low-value species with less diverse life history characteristics (e.g. pink salmon). We also posit that there may be stronger trade-offs among species in salmon fisheries relative to terrestrial agriculture. Even for a single-permit type, different salmon species have different spatial and temporal distributions and can require slightly different fishing gears or methods. Fishers that adopt strategies (gears, areas) that allow a diverse salmon catch may experience trade-offs of reduced catches compared to specialist fishers that target large amounts of fewer species. As economic theory predicts for individuals generally, fishers who target fewer species may also be more efficient and benefit from accumulated knowledge associated with specialization (Becker & Murphy, 1992; Krugman, 1979; Romer, 1987).

Protecting individuals and coastal communities from future economic shocks is complex, particularly as environmental variability increases. Factors including the future abundance and species composition, the spatial distribution of fish, prices and demand, or hatchery programmes may all contribute to uncertainty. The available management tools that may be helpful in countering economic risk vary, depending on the management body or countries involved. For species managed under property rights based systems (e.g. catch shares), it is important to consider future flexibility in how individuals can diversify, barriers preventing them from doing so, and potential benefits that may arise from specializing. Tools such as crop insurance programmes used to buffer incomes of terrestrial farmers have seen limited use in fisheries (Herrmann, Greenberg, Hamel, & Geier, 2004;

Mumford, Leach, Levontin, & Kell, 2009). Another option for offsetting risk is government support, such as fishery disaster assistance programs. In the USA, these programmes are federally funded through the Magnusson Stevens Act. Over the course of our study 1975–2016, salmon fishery disasters were declared in Alaska in 1997–2000, 2009–2012 and 2016, totalling more than $100 million dollars. As some of these salmon fisheries have become more specialized, management may benefit from future work into how specialization affects the likelihood of disasters occurring, as well as how disaster funding affects the participation and revenue of individual fishers.

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AUTHORS’ CONTRIBUTIONS

E.W., A.B., R.B. and O.S. secured funding for this project; CFEC data were provided by J.S. and J.W. with assistance from R.B.; E.W. and S.A. did the modelling, with E.W., S.A., O.S. and J.W. producing the main and supplemental figures, with guidance from J.S. and R.B. All authors contributed to performing preliminary analyses as part of the NCEAS workshops, critically assisted in writing drafts and gave final approval for publication.

DATA ACCESSIBILITY

The raw fish ticket data (individual catches of individual people) that support the findings of this study, although confidential, are available from the Commercial Fisheries Entry Commission (https://www.cfec.state.ak.us/). Compiled fish ticket data, along with all data related to the hatchery analyses, and all codes, are available at Zenodo: https://doi.org/10.5281/zenodo.1041758 (Ward, Anderson, et al., 2017).

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REFERENCES

ADFG (2007). *Catch, effort, and value statewide harvest. Recent years harvest statistics. Blue sheets*. Alaska Department of Fish and Game: Juneau, AK.

Aguilar, J., Gramig, G. G., Hendrickson, J. R., Archer, D. W., Forcella, F., & Liebig, M. A. (2015). Crop species diversity changes in the United States: 19782012. *PLoS ONE*, *10*, e0136580. https://doi.org/10.1371/journal.pone.0136580

Amoroso, R. O., Tillotson, M. D., & Hilborn, R. (2017). Measuring the net biological impact of fisheries enhancement: Pink salmon hatcheries can increase yield, but with apparent costs to wild populations. *Canadian Journal of Fisheries and Aquatic Sciences*, *74*, 1233–1242. https://doi.org/10.1139/cjfas-2016-0334

Anderson, S. C., Ward, E. J., Adkison, M. D., Beaudreau, A. H., Brenner, R. E., Haynie, A. C., … Watson, J. T. (2017). Benefits of diversification and risks of changing strategies for individual fishers. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 10797–10802. https://doi.org/10.1073/pnas.1702506114

Becker, G. S., & Murphy, K. M. (1992). The division of labor, coordination costs, and knowledge. *The Quarterly Journal of Economics*, *107*, 1137–1160. https://doi.org/10.2307/2118383

Boyce, J., Herrmann, M., Bischak, D., & Greenberg, J. (1993). The Alaska salmon enhancement program: A cost/benefit analysis. *Marine Resource Economics*, *8*, 293–312. https://doi.org/10.1086/mre.8.4.42731363

Bradshaw, B., Dolan, H., & Smit, B. (2004). Farm-level adaptation to climatic variability and change: Crop diversification in the Canadian prairies. *Climatic Change*, *67*, 119–141. https://doi.org/10.1007/s10584-004-0710-z

Brooks, J. (1976). *Alaska salmon fisheries plan*. Anchorage, AK: Alaska Department of Fish and Game.

Carpenter, B., Gelman, A., Hoffman, M. D., Lee, D., Goodrich, B., Betancourt, M., … Riddell, A. (2017). Stan: A probabilistic programming language. *Journal of Statistical Software*, *76*. https://doi.org/10.18637/jss.v076.i01

Cline, T. J., Schindler, D. E., & Hilborn, R. (2017). Fisheries portfolio diversification and turnover buffer Alaskan fishing communities from abrupt resource and market changes. *Nature Communications*, *8*, 14042. https://doi.org/10.1038/ncomms14042

Dangel, J., & Jones, J. (1988). *Southeast Alaska pink salmon total escapement and stream life studies*. Regional Information Report. Juneau, AK: Alaska Department of Fish and Game, Division of Commercial Fisheries. http://www.adfg.alaska.gov/FedAidPDFs/rir.1j.1988.24.pdf

Di Falco, S., & Perrings, C. (2003). Crop genetic diversity, productivity and stability of agroecosystems. A theoretical and empirical investigation. *Scottish Journal of Political Economy*, *50*, 207–216. https://doi.org/10.1111/1467-9485.5002006

Fissel, B., Dalton, M., Felthoven, R., Garber-Yonts, B., Haynie, A., Kasperski, S., … Sparks, K. (2016). *Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands area: Economic status of the groundfish fisheries off Alaska, 2015*. Seattle, WA: Resource Ecology; Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service. https://www.afsc.noaa.gov/refm/docs/2016/economic.pdf

Gelman, A., & Rubin, D. (1992). Inference from iterative simulation using multiple sequences. *Statistical Science*, *7*, 457–511. https://doi.org/10.1214/ss/1177011136

Herrmann, M., Greenberg, J., Hamel, C., & Geier, H. (2004). Extending federal crop insurance programs to commercial fisheries: The case of Bristol Bay, Alaska, Sockeye Salmon. *North American Journal of Fisheries Management*, *24*, 352–366. https://doi.org/10.1577/M02-086.1

Hilborn, R. (1992). Hatcheries and the future of salmon in the Northwest. *Fisheries*, *17*, 5–8. https://doi.org/10.1577/1548-8446(1992)017<0005:HATFOS>2.0.CO;2

Hilborn, R., & Eggers, D. (2001). A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska: Response to comment. *Transactions of the American Fisheries Society*, *130*, 720–724. https://doi.org/10.1577/1548-8659(2001)130<0720:AROTHP>2.0.CO;2

Himes-Cornell, A., & Hoelting, K. (2015). Resilience strategies in the face of short- and long-term change: Out-migration and fisheries regulation in Alaskan fishing communities. *Ecology and Society*, *20*, 9. https://doi.org/10.5751/es-07074-200209

Hoffman, M. D., & Gelman, A. (2014). The No-U-Turn sampler: Adaptively setting path lengths in Hamiltonian Monte Carlo. *Journal of Machine Learning Research*, *15*, 1593–1623.

Jost, L. (2006). Entropy and diversity. *Oikos*, *113*, 363–375. https://doi.org/10.1111/j.2006.0030-1299.14714.x

Kasperski, S., & Holland, D. S. (2013). Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, 2076–2081. https://doi.org/10.1073/pnas.1212278110

Knapp, G. (2012). *Trends in Alaska salmon markets*. Anchorage, AK: University of Alaska Anchorage. http://www.iser.uaa.alaska.edu/people/knapp/personal/

Knapp, G., Roheim, C., & Anderson, J. (2007). *The great salmon run: Competition between wild and farmed salmon*. Washington, DC: TRAFFIC North America, World Wildlife Fund.

Krugman, P. R. (1979). Increasing returns, monopolistic competition, and international trade. *Journal of International Economics*, *9*, 469–479. https://doi.org/10.1016/0022-1996(79)90017-5

Leber, K. M., Kitada, S., Blankenship, H. L., & Svasand, T. (2008). *Stock enhancement and sea ranching: Developments, pitfalls and opportunities*. Oxford, UK: John Wiley & Sons.

Loring, P. A. (2016). Toward a theory of coexistence in shared social-ecological systems: The case of Cook Inlet salmon fisheries. *Human Ecology*, *44*, 153–165. https://doi.org/10.1007/s10745-016-9806-0

Mahnken, C., Ruggerone, G., Waknitz, W., & Flagg, T. (1998). A historical perspective on salmonid production from Pacific rim hatcheries. *North Pacific Anadromous Fish Commission Bulletin*, *1*, 38–53.

Mishra, A., El-Osta, H., Morehart, M., Johnson, J., & Hopkins, J. (2002). *Income, wealth, and the economic well-being of farm households*. Agricultural Economic Report. Washington, DC: Farm Sector Performance; Well-Being Branch, Resource Economics Division, Economic Research Service, U.S. Department of Agriculture. https://www.ers.usda.gov/publications/pub-details/?pubid=41464

Mueter, F. J., Peterman, R. M., & Pyper, B. J. (2002). Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus* spp.) in northern and southern areas. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*, 456–463. https://doi.org/10.1139/f02-020

Mumford, J. D., Leach, A. W., Levontin, P., & Kell, L. T. (2009). Insurance mechanisms to mediate economic risks in marine fisheries. *ICES Journal of Marine Science*, *66*, 950–959. https://doi.org/10.1093/icesjms/fsp100

Office of Science and Technology. (2016). *Fisheries Economics of the United States in 2014*. NOAA Technical Memorandum, Economics; Social Analysis Division. NOAA Technical Memorandum NMFS-F/SPO-163.

Purdy, B. M., Langemeier, M., & Featherstone, A. (1997). Financial performance, risk, and specialization. *Journal of Agricultural and Applied Economics*, *29*, 149–161. https://doi.org/10.1017/S107407080000763X

Quinn, T. P. (2005). *The behavior and ecology of Pacific salmon and trout*. Seattle, WA: University of Washington Press.

R Core Team. (2017). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Romer, P. M. (1987). Growth based on increasing returns due to specialization. *American Economic Review*, *77*, 56–62.

Ruggerone, G. T., & Connors, B. M. (2015). Productivity and life history of sockeye salmon in relation to competition with pink and sockeye salmon in the North Pacific Ocean. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*, 818–833. https://doi.org/10.1139/cjfas-2014-0134

Schindler, D. E., Hilborn, R., Chasco, B., Boatright, C. P., Quinn, T. P., Rogers, L. A., & Webster, M. S. (2010). Population diversity and the portfolio effect in an exploited species. *Nature*, *465*, 609–612. https://doi.org/10.1038/nature09060

Sethi, S. A., Dalton, M., & Hilborn, R. (2012). Quantitative risk measures applied to Alaskan commercial fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*, 487–498. https://doi.org/10.1139/f2011-170

Sethi, S. A., Reimer, M., & Knapp, G. (2014). Alaskan fishing community revenues and the stabilizing role of fishing portfolios. *Marine Policy*, *48*, 134–141. https://doi.org/10.1016/j.marpol.2014.03.027

Smyth, G. K. (1989). Generalized linear models with varying dispersion. *Journal of the Royal Statistical Society. Series B (Methodological)*, *51*, 47–60.

Stan Development Team. (2015). *Stan modeling language user's guide and reference manual, version 2.10.0*. Retrieved from http://mc-stan.org

Stan Development Team. (2017). *RStan: The R interface to Stan. R package version 2.16.2*. Retrieved from http://mc-stan.org

Stopha, M. (2016). *Alaska fisheries enhancement annual report 2015*. Anchorage, AK: Alaska Department of Fish; Game Division of Commercial Fisheries. http://www.adfg.alaska.gov/FedAidPDFs/RIR.5J.2016.03.pdf

United States Bureau of Economic Analysis. (2017). *Gross domestic product: Implicit price deflator [GDPDEF]*. https://fred.stlouisfed.org/series/GDPDEF

Ward, E. J., Adkison, M. D., Couture, J., Dressel, S. C., Litzow, M. A., Moffitt, S., … Brenner, R. E. (2017). Evaluating signals of climate, oil spill impacts, and interspecific interactions in Pacific salmon and Pacific herring populations in Prince William Sound and Copper River, Alaska. *PLoS ONE*, *12*, e0172898. https://doi.org/10.1371/journal.pone.0172898

Ward, E. J., Anderson, S. C., Shelton, A. O., Brenner, R. E., Adkison, M. D., Beaudreau, A. H., … Williams, B. C. (2017). Data from: Effects of increased specialization on revenue of Alaskan salmon fishers over four decades. *Zenodo*, https://doi.org/10.5281/zenodo.1041758

Wertheimer, A. C., Smoker, W. W., Joyce, T. L., & Heard, W. R. (2001). Comment: A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. *Transactions of the American Fisheries Society*, *130*, 712–720. https://doi.org/10.1577/1548-8659(2001)130<0712:CAROTH>2.0.CO;2

Western, B., & Deidre, B. (2009). Variance function regression for studying inequality. *Sociological Methodology*, *39*, 293–325. https://doi.org/10.1111/j.1467-9531.2009.01222.x

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