Grand title

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Abstract

Key words

Introduction

Diverse resource portfolios can reduce revenue variability and financial risk incurred due to the large fluctuations in productivity and profitability of exploited natural populations (Kasperski and Holland 2013). Variability in fishery revenue declines for individuals (Anderson et al. 2017), vessels (Kasperski and Holland 2013), and communities (Sethi et al. 2014, Himes-Cornell and Hoelting 2015, Cline et al. 2017) when fishers and communities maintain a diverse portfolio of fishing activities by targeting different species or geographic areas. However, the ability to build diverse fishing portfolios has declined as limited access and catch share programs have increasingly constrained access to fisheries. This is particularly the case for younger fishers who were not gifted fishing permits when access first became limited (Kasperski and Holland 2013, Himes-Cornell and Hoelting 2015, Holland and Kasperski 2016, Holland et al. 2017).

The ecological dynamics and life histories of the populations that comprise resource portfolios mediate the extent to which diverse portfolios benefit income patterns and risk. Populations can vary synchronously, independently, or asynchronously of one another. These patterns are driven by myriad factors such as X, Y, and Z. Populations that vary asynchronously or independently of one another yield a more temporally stable aggregate biomass than populations that vary synchronously (Doak et al. 1998), and this stability in biomass can lead to greater stability in the revenue that the portfolio of populations generates (Hilborn et al. 2003, Schindler et al. 2010). Second, variability itself can be driven by life history. Long-lived species with “slow” life histories tend to exhibit smaller interannual variations in abundance than “fast” short-lived species (cite). Finally, phenology often determines timing of the fishing seasons so that populations are protected during periods that are particularly important for reproduction and growth (e.g., molting, carrying of egg sacs). Portfolios that both stabilize *and* increase revenue should take advantage of asynchrony not only in productivity, but also in seasonality, to enable fuller use of capital. Both human (cite) and natural (Schindler et al. 2013) predators can benefit from taking advantage of these phenological portfolios.

Management decisions and responses to unusual events can impact the value of diversification strategies and create uncertainty for both fishers and managers in understanding the desirability of alternative business and fishery management strategies. Some fisheries have variable opening dates depending on the condition or size of animals. For example, West Coast Dungeness crab (*Metacarcinus magister*) fisheries are only opened following fall molting once crabs have sufficient meat fullness and do not contain excessive levels of demoic acid associated with harmful algal blooms (HABs) (<http://www.psmfc.org/crab/>). In 2016, the Dungeness crab fisheries on the West Coast of the US were delayed over four months due to demoic acid levels, causing a cascade of changes in fishery participation both during the closure and in the spring when crab fishing had normally ended. As a second example, West Coast pink shrimp (*Pandalus borealis*) seasons are sometimes delayed if age-one shrimp are too small (cite). Programs implemented to “rationalize” fisheries by forcing or incentivizing consolidation can increase profitability within a fishery, but may raise the cost of entry and change the seasonality of the fishery. For example, a catch share system can transform a derby fishery that lasted days or weeks into a year-round fishery (cite). Catch shares can stabilize income for participants who remain in the fishery, but revenue variability can increase for those who exit the catch share fishery by decreasing the diversity of their fishing portfolio (Holland et al. 2017).

The California Current Large Marine Ecosystem (CCLME) provides an ideal model system to explore how ecological dynamics and management decisions combine to impact the profitability and risk of alternative fishing portfolios and overall fishery performance. Many fisheries in the CCLME are highly interdependent, sharing linkages through both exposure to common environmental drivers and cross-participation of fishers. Climate variability is a strong component of the CCLME (Schwing et al. 2010), especially due to ENSO events (Jacox et al. 2016) and the Pacific Decadal Oscillation (Mantua et al. 1997, Hare and Mantua 2000). In addition, physical changes associated with warming and ocean acidification could increase and transform previous patterns of climate variability (Black et al. 2014). Climate cycles and oceanic conditions influence the productivity of many commercially valuable species across scales through impacts to recruitment, growth and spatial distribution (Black et al. 2010, Schwing et al. 2010, Hazen et al. 2013, Shanks 2013, Stachura et al. 2014, Stawitz et al. 2015), indirectly linking their dynamics. Participation of fishers in multiple fisheries within the California Current provides additional connectivity of dynamics among the component populations. Although the strength of this cross-participation varies among fishing ports, it represents an important linkage at the coastwide scale (Fuller et al. 2017).

We develop a simulation model that is roughly based on the fisheries for three key species in the CCLME. We use this model to explore how synchrony of productivity combined with ease of access and movement among fisheries combine to affect profitability and variability in income for fishers. Understanding the consequences of management strategies in conjunction with the ecological dynamics of the fish stocks and the participation decisions of fishers is daunting. Simulation models that capture the key characteristics of this system can help overcome data limitations and provide insights into the dynamics of these complex socioecological systems. We simulated annual recruitment and population dynamics and weekly fishery participation decisions for six permit portfolios that target some combination of Dungeness crab (*Metacarcinus magister*), Chinook salmon (*Oncorhynchus tshawytscha*) and groundfish (characterized by Sablefish: *Anoplopoma fimbria*) off the U.S West Coast. We used the model to vary the number of fishers holding a diverse permit portfolio under alternative correlations in recruitment of the populations. We consider how changes in the ease of access affect the profitability and variability in profits for the different fleets at individual and aggregated levels when recruitment among the populations is synchronous, asynchronous, or independent.

Methods

We built a simulation model for the three species which are linked by cross-participation and productivity dynamics. The fisheries for these species are among the largest on the U.S. West Coast in terms of both number of participants and revenue generated (cite). We simulated fisheries for 50 years and ran X 50-year simulations under each scenario. The model was written in R version 3.5.1 (R Core Team 2018).

*Focal fisheries*

Despite limits on the number of participants, Dungeness crab fisheries are derbies in which nearly all legal-size crabs are caught in a matter of weeks, and catch rates decline rapidly as fishers deplete the population. Most fishers exit before the fishery legally closes and participate in other fisheries or outside work. The timing of this exit varies substantially among years due to variability in the opening dates, abundance of crab, and individual cost incentives. Crab recruitment is largely driven by environmental conditions during the larval phase, and they display little to no stock-recruit relationship (cite), so we modeled recruitment as a random lognormal variable with temporal autocorrelation to emulate observed regime-like patterns, described below. The biomass available to the fishery is simply that corresponding to the year’s recruitment. We assume crab fisheries open on December 1 (start of the model year) and close on August 14.

Salmon fisheries are also highly variable and have been subject to several large closures in recent years designed to protect threatened or endangered wild stocks that mix with the hatchery fish that make up most of the ocean fishery harvest (Richerson and Holland 2017, Richerson et al. 2018). Because the majority of the ocean salmon harvest is of hatchery origin, biomass available to the fishery depends mainly on hatchery production and ocean survival rates (cite). Note many smolts are trucked directly to the estuary, eliminating variability in freshwater survival (cite). Thus, salmon availability also does not follow a stock-recruit relationship, and we again modeled recruitment as a random lognormal variable with temporal autocorrelation where biomass available to the fishery is equal to recruitment. We assume salmon fisheries open on May 1 and close on October 31.

The groundfish fishery is relatively stable in comparison to crab and salmon, as it targets longer-lived species and exerts much lower fishing mortality rates (e.g., Johnson et al. 2015). Because groundfish are subject to depletion across years, we modeled the populations using a delay-difference model, described below. Groundfish fisheries operate year-round.

*Fishery participation model*

Each week of the year, vessels in the model each consider their costs and anticipated revenue and decide whether it would be profitable to fish. If it was profitable to fish in more than one fishery, they also chose which fishery to participate in.

Costs of fishing were divided into annual fixed costs for each species *s* () that were automatically incurred every year (e.g., permits, boat and gear maintenance) and weekly variable costs for each species *s* and vessel *v* (*cs,v*) that were only incurred if a vessel chose to fish for a particular species in a given week (e.g., fuel, bait, labor). Variable costs varied among vessels according to a lognormal distribution to mimic disparities in fishing efficiency and introduce differences in participation decisions among vessels during the season. To maintain equilibrium in fishery participation (i.e., on average no entry or exit) and permit costs, we set total costs in an average recruitment year equal to total revenue for a marginal fisher (95th percentile of variable cost distribution) who might be considering entry into the fishery. We ensured this condition by using a root-finding routine that projected a single fishery in an average year. The routine solved for the mean variable cost given the profitability constraint, fixed costs, and catchability. To avoid monte carlo error during the root-finding phase, vessel-specific variable costs were assigned based on quantiles from the inverse lognormal cumulative density function. For actual simulations, these costs were drawn randomly by vessel, but held constant over time. For simplicity, this variable cost calculation was done independently for each fishery (i.e., vessels did not have other fishing options during the calculations), and was based on a fleet consisting of the same number of vessels as held permits for the fishery in the baseline scenario (Table 2).

Fishers were assumed to have perfect knowledge of the available biomass each week, and catchability was held constant with no interference among vessels. Revenue for a vessel fishing for species *s* in week *w* of year *y,* *rs,y,w* was then:

where *qs* is the catchability of species *s* (proportion of the population harvested by one vessel in one week) and *Ps,y,w* is the price per unit biomass of species *s* in week *w* of year *y*. Prices were held constant for groundfish and salmon, so fishers also had perfect knowledge of the revenue and profit they would earn in a week for those populations. A linear demand function was built for crab to better mimic real dynamics of the Dungeness crab fishery. This function led to much higher population depletion by the end of the season and increased the temporal overlap between the crab and salmon fisheries. Prices for Dungeness crab (*Pd,y,w*, subscript *d* for Dungness)increased linearly as catches fell once total weekly catches (*Cd,y,w*) were below 10% of average recruitment ():

This price function is continuous when , as we assumed. Fishers used the crab prices from the previous week to calculate expected revenue and profit for the upcoming week. In the first week of the year, we assumed fishers already had perfect knowledge of recruitment, and they calculated expected prices based on the demand function, assuming that every vessel holding a crab permit would fish for crab in the first week. Crab prices were held constant at 1 in the algorithm that tunes costs.

Each week every fisher then calculated their expected marginal profits (*rs,y,w* – *cs,v*) for each fishery that was open and for which they held a permit, and either fished in the most profitable fishery or, if no fishery was profitable (*rs,y,w* – *cs,v* <0), did not fish that week. For vessels holding multiple permits, variable costs across fisheries were correlated (i.e., efficiency across fisheries is correlated for each vessel at a correlation of *ρc*).

*Salmon and crab population models*

Salmon and crab populations were modeled as random recruitment deviations with no dynamics explicitly linking abundances from one year to the next. Thus, recruitment for species *s* in year *y* was:

where  is average recruitment for species *s* and *εy,s* is an autocorrelated normal random variable. That is, when recruitment is independent among populations,

where *ϕs* is the strength of autocorrelation (between zero and one) for species *s*, *σR,s* is the unconditional standard deviation of *εs*,andthe second term in the mean is a bias correction to ensure that

*Groundfish population model*

The groundfish population is simulated based on a Deriso-Schnute delay-difference model with a Beverton-Holt stock-recruit relationship (Schnute, 1985). This allows for changes in age structure, an advance from simpler surplus production models, but restrictively assumes selectivity and maturity are knife-edged and occur at the same age (Hilborn and Walters 1992, Quinn and Deriso 1999). Although biomass dynamics in this model can be simulated with a single complex equation, for ease, we equivalently modeled both abundance (*N*) and biomass (*B*) (Hilborn and Walters 1992). For comparability with the crab and salmon populations, we assumed these dynamics occurred at an annual time scale:

where *Sy* is total per capita survival in year *y*; *α* and *β* are the intercept and slope, respectively, of a Ford-Walford plot (i.e., plot of weight at age vs. weight at age - 1); *ωk* is the weight at age *k*; *k* is the age at both recruitment to the fishery and maturity; and *Ry,g* is the recruitment to the fishery of groundfish (subscript *g*) in year *y*. We assumed a Beverton-Holt stock-recruit relationship using the steepness parameterization, so that:

where *h*, *R0*, and *B0* are steepness (percent of unfished recruitment occurring at 20% of unfished biomass, i.e., “resilience”), unfished recruitment, and unfished biomass, respectively, *Hy* is the proportion of the biomass that was harvested in year *y*, and *εy,g* is a random recruitment deviation in year *y* for groundfish modeled in the same way as described in the previous section. This model formulation presumes that reproduction occurs after fishing and before natural mortality. Unfished biomass is calculated based on equilibrium conditions as *R0*/*κH=0* where *κ* is the following growth-survival constant:

The growth parameters *α* and *β* were calculated by taking the weight at age from the stock assessment’s age-length and length-weight relationships and estimating a linear regression through the resulting points (which are almost, but not exactly, linear). We fixed weight at recruitment (age 4), to 1, as with salmon and crab.

Because the groundfish population dynamics respond to the fishery dynamics, tuning the fishery parameters was more a complicated process for groundfish. First, catchability was set so that when all 201 vessels with groundfish permits participate in fishery 40 weeks of the year, yield is equal to the level that leads the population to equilibrate at 40% of the unfished biomass. We then fixed the variable cost and solved for the fixed cost such that the 5th percentile vessel had no net profit when the population equilibrated at 40% of unfished biomass. In addition, we checked that the lowest quantile vessel would still cover its variable costs in the final week of the year, ensuring that all vessels would in fact fish every week. We assumed the population had equilibrated at 40% of its unfished biomass at the start of each simulation, and visually checked that groundfish biomass did not display a tendency to increase or decrease over the simulations.

*Scenarios*

The first set of scenarios varied the correlation in recruitment deviations among the three populations. When recruitment was correlated among species, recruitment deviations became multivariate normal random variables:

where indicates elementwise multiplication, bold symbols are vectors comprised of the value of that variable for each species, and Σ is the covariance matrix. The diagonal of Σ was defined by the variance term of the normal distribution in equation X. The off-diagonals were defined as:

where *ρR,i,j* is the correlation in log recruitment deviations between species *i* and *j*. Note when recruitment among all populations is independent, as it is in the baseline parameterization, *ρR,i,j* = Σ*i,j* = 0 for all *i* and *j*, and equations X and Y become equivalent. We tested scenarios with *ρR,i,j* = -0.5, 0, and 0.5, using the same value for all three pairwise correlations (i.e., *ρR,i,j = ρR*). We tried using a magnitude greater than 0.5 but it is not mathematically possible to simulate three random variables that all have stronger negative correlations.

The second set of scenarios varied the number of vessels holding permits for a single fishery versus multiple fisheries (Table 2). Finally, we tested the interaction between synchrony and permit access by running the easy and hard access scenarios under both synchronous and asynchronous recruitment.

For each 50-year simulation, we calculated the mean and standard deviation of both profit and revenue and the coefficient of variation of revenue for each vessel. We also computed those same statistics for total revenue and profits summed over the entire fleet, and we computed the mean, standard deviation, and coefficient of variation for total revenue aggregated over each species.

A note!

I also tried a scenario when you delay the opening of the crab fishery by 16 weeks with 25% probability each year (i.e., assume demoic acid closures become more frequent). It did work in that you saw people entering the salmon fishery late in years the crab fishery was delayed. But nothing really happened to the average revenue or revenue variability! This null result is kind of interesting, but the easy counter is that the model is just wrong and ill-suited to the exercise. I think to do this analysis justice it would require a bit more poking and prodding at the model, and this paper would turn into a monstrosity. Maybe a good MS thesis! But I am also open to your thoughts!

Table 1

|  |  |  |
| --- | --- | --- |
| **Symbol** | **Description** | **Value (if set)** |
| *y* | Year index |  |
| *w* | Week index |  |
| *s* | Species index |  |
| *v* | Vessel index |  |
| *Ry,s* | Recruitment |  |
| *rs,y,w* | Revenue |  |
| *By* | Biomass (groundfish only) |  |
| *Ny* | Abundance (groundfish only) |  |
| *Cs,y,w* | Catch |  |
| *Ps,y,w* | Price per unit biomass |  |
|  | Annual fixed costs | Crab: 0.0025, salmon: 0.0001, groundfish: tuned internally |
| *cs,v* | Weekly variable costs | Crab: tuned internally, salmon: tuned internally, groundfish: 0.00002 |
| *Sy* | Total survival (groundfish only) |  |
| *M* | Natural mortality rate (groundfish only) | 0.07 yr-1 |
| *α, β* | Intercept, slope, respectively, of Ford-Walford plot (i.e., weight at agevs. age – 1) (groundfish only) | 0.459, 0.736 |
|  |  |  |
| *R0­* | Unfished recruitment (groundfish only) | 0.5 |
| *B0* | Unfished biomass (groundfish only) |  |
| *h* | Stock-recruit steepness (“resilience”) (groundfish only) | 0.6 |
| *Hy* | Harvest rate (groundfish only) |  |
|  |  |  |
| *k* | Age at recruitment (groundfish only) | 4 |
| *ωk* | Weight at age *k* (i.e., recruitment) | 1 (all 3 species) |
| *σR,s* | Standard deviation of log(*R*) | 0.555 (all 3 species), CV = 0.6 |
| *εy,s* | Log of recruitment deviation |  |
| *ϕs* | Autocorrelation parameter | 0.3 (all 3 species) |
|  | Average recruitment (crab and salmon) | 1 (both species) |
| *ρc* | Correlation of variable costs for a vessel | 0.7 |
| *σc* | Standard deviation of log(*c*) | 0.149, CV = 0.15 |
| *qs* | Catchability | Crab: 0.0005, salmon: 0.00005, groundfish: tuned internally |
| *ρR,i,j* | Correlation of log(*R*) between species *i* and *j* | -0.5, 0, 0.5 (baseline = 0) |

Table 2

|  |  |  |  |
| --- | --- | --- | --- |
| **Permit portfolio** | **Easy access vessel count** | **Medium access vessel count (baseline)** | **Hard access vessel count** |
| Crab only | 25 | 67 | 109 |
| Salmon only | 25 | 67 | 109 |
| Groundfish only | 25 | 67 | 109 |
| Crab-salmon | 109 | 67 | 25 |
| Crab-groundfish | 109 | 67 | 25 |
| Crab-salmon-groundfish | 109 | 67 | 25 |
| Total number of vessels | 402 | 402 | 402 |

Results

More access:

1. Decreases average profits and revenue of individuals within a fleet: less fish per person
2. Decreases crab revenue because derby fishery floods markets, prices are low
3. Increases salmon and groundfish revenue because more permits means more fish caught
4. Increases variability of salmon and groundfish revenue (CV & SD)
5. Decreases inequality in mean revenue because more people have access to high value fishery
6. Decreases profit/revenue SD within a fleet for anyone who has a crab permit
7. Decreases revenue CV across all individuals (except also eliminates groundfish specialist hump near zero)
8. Decreases *spread* of revenue CV distribution for crab and crab/salmon fleets— decreases instances of high *and* low variability individuals/simulations (which?)
9. Complicated impact on total summed revenue/profits. No/minimal change in variability.

Asynchrony:

1. No impact on mean profit/revenue of individuals
2. No impact on mean or variability of profit/revenue by species
3. Decreases individual profit/revenue variability for those in fleets with crab & salmon in permit portfolio.
4. Decreases total summed profit/revenue variability

Note that looking at the interaction of synchrony and access generally results in intuitive additive results.

Discussion

1. Summary of key results
2. Tradeoff between revenue quantity and variability. Catch shares reduce variability *within* year, but erosion of portfolios can increase variability *among* years.
3. Different patterns at different levels of aggregation (entire fleet, stock, individual). Choose the right metric.
4. Life history + synchrony patterns jointly determine the best portfolios to reduce variability.
5. This kind of model is fairly novel.
6. Caveats
7. Future research, broad conclusions.

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Literature Cited

Anderson, S. C., E. J. Ward, A. O. Shelton, M. D. Adkison, A. H. Beaudreau, R. E. Brenner, A. C. Haynie, J. C. Shriver, J. T. Watson, and B. C. Williams. 2017. Benefits and risks of diversification for individual fishers. Proceedings of the National Academy of Sciences 114:10797–10802.

Black, B. A., I. D. Schroeder, W. J. Sydeman, S. J. Bograd, and P. W. Lawson. 2010. Wintertime ocean conditions synchronize rockfish growth and seabird reproduction in the central California Current ecosystem. Canadian Journal of Fisheries and Aquatic Sciences 67:1149–1158.

Black, B. A., W. J. Sydeman, D. C. Frank, D. Griffin, D. W. Stahle, M. García-Reyes, R. R. Rykaczewski, S. J. Bograd, and W. T. Peterson. 2014. Six centuries of variability and extremes in a coupled marine-terrestrial ecosystem. Science 345:1498–1502.

Cline, T. J., D. E. Schindler, and R. Hilborn. 2017. Fisheries portfolio diversification and turnover buffer Alaskan fishing communities from abrupt resource and market changes. Nature Communications 8:14042.

Doak, D. F., D. Bigger, E. K. Harding, M. A. Marvier, R. E. O’Malley, and D. Thomson. 1998. The Statistical Inevitability of Stability‐Diversity Relationships in Community Ecology. The American Naturalist 151:264–276.

Fuller, E. C., J. F. Samhouri, J. S. Stoll, S. A. Levin, and J. R. Watson. 2017. Characterizing fisheries connectivity in marine social–ecological systems. ICES Journal of Marine Science 74:2087–2096.

Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103–145.

Hazen, E. L., S. Jorgensen, R. R. Rykaczewski, S. J. Bograd, D. G. Foley, I. D. Jonsen, S. A. Shaffer, J. P. Dunne, D. P. Costa, L. B. Crowder, and B. A. Block. 2013. Predicted habitat shifts of Pacific top predators in a changing climate. Nature Climate Change 3:234–238.

Hilborn, R., T. P. Quinn, D. E. Schindler, and D. E. Rogers. 2003. Biocomplexity and fisheries sustainability. Proceedings of the National Academy of Sciences 100:6564–6568.

Hilborn, R., and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Chapman and Hall, New York.

Himes-Cornell, A., and K. Hoelting. 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.

Holland, D. S., and S. Kasperski. 2016. The Impact of Access Restrictions on Fishery Income Diversification of US West Coast Fishermen. Coastal Management 44:452–463.

Holland, D. S., C. Speir, J. Agar, S. Crosson, G. DePiper, S. Kasperski, A. W. Kitts, and L. Perruso. 2017. Impact of catch shares on diversification of fishers’ income and risk. Proceedings of the National Academy of Sciences 114:9302–9307.

Jacox, M. G., E. L. Hazen, K. D. Zaba, D. L. Rudnick, C. A. Edwards, A. M. Moore, and S. J. Bograd. 2016. Impacts of the 2015–2016 El Niño on the California Current System: Early assessment and comparison to past events. Geophysical Research Letters 43:7072–7080.

Johnson, K. F., M. B. Rudd, M. Pons, C. A. Akselrud, Q. Lee, M. A. Haltuch, and O. S. Hamel. 2015. Status of the U.S. sablefish resource in 2015:377.

Kasperski, S., and D. S. Holland. 2013. Income diversification and risk for fishermen. Proceedings of the National Academy of Sciences 110:2076–2081.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069–1079.

Quinn, T. J., and R. B. Deriso. 1999. Quantitative fish dynamics. Oxford University Press, New York.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Richerson, K., and D. S. Holland. 2017. Quantifying and predicting responses to a US West Coast salmon fishery closure. ICES Journal of Marine Science 74:2364–2378.

Richerson, K., J. Leonard, and D. S. Holland. 2018. Predicting the economic impacts of the 2017 West Coast salmon troll ocean fishery closure. Marine Policy 95:142–152.

Schindler, D. E., J. B. Armstrong, K. T. Bentley, K. Jankowski, P. J. Lisi, and L. X. Payne. 2013. Riding the crimson tide: mobile terrestrial consumers track phenological variation in spawning of an anadromous fish. Biology Letters 9:20130048.

Schindler, D. E., R. Hilborn, B. Chasco, C. P. Boatright, T. P. Quinn, L. A. Rogers, and M. S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. Nature 465:609–612.

Schwing, F. B., R. Mendelssohn, S. J. Bograd, J. E. Overland, M. Wang, and S. Ito. 2010. Climate change, teleconnection patterns, and regional processes forcing marine populations in the Pacific. Journal of Marine Systems 79:245–257.

Sethi, S. A., M. Reimer, and G. Knapp. 2014. Alaskan fishing community revenues and the stabilizing role of fishing portfolios. Marine Policy 48:134–141.

Shanks, A. L. 2013. Atmospheric forcing drives recruitment variation in the Dungeness crab (Cancer magister), revisited. Fisheries Oceanography 22:263–272.

Stachura, M. M., T. E. Essington, N. J. Mantua, A. B. Hollowed, M. A. Haltuch, P. D. Spencer, T. A. Branch, and M. J. Doyle. 2014. Linking Northeast Pacific recruitment synchrony to environmental variability. Fisheries Oceanography 23:389–408.

Stawitz, C. C., T. E. Essington, T. A. Branch, M. A. Haltuch, A. B. Hollowed, and P. D. Spencer. 2015. A state-space approach for detecting growth variation and application to North Pacific groundfish. Canadian Journal of Fisheries and Aquatic Sciences 72:1316–1328.