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Original Article

Quantifying and predicting responses to a US West Coast salmon fishery closure

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As anthropogenic changes interact with natural climate cycles, the variability of marine ecosystems is likely to increase. Changes in productivity of particular fisheries might be expected to lead not only to direct impacts within a fishery but to economic and ecological effects on other fisheries if there is substantial cross-participation by fishers. We use data from the US West Coast salmon troll fishery before, during, and after a large-scale closure to illustrate how altered resource availability influences the behaviour of fishing vessels in heterogeneous ways. We find that vessels were less likely to participate in fishing of any type during the closure, with >40% of vessels ceasing fishing temporarily and 17% exiting permanently. Vessels that were more dependent on salmon were more likely to cease fishing while more diversified vessels were more likely to continue. In spite of a high level of cross-participation, we find limited evidence that vessels increased their participation in other fisheries to offset lost salmon revenue. Ports that obtained more of their revenue from salmon troll vessels saw larger decreases in their revenue during the closure. Ocean conditions from 2013 to 2015 suggest the possibility of another highly restricted salmon fishing season in 2017. Our models predict that such restrictions would cause another economic disaster and lead to a large fraction of vessels exiting fishing but suggest that effects on fisheries linked by cross-participation are likely to be low.

Keywords: California Current, climate variability, cross-participation, fishing behaviour, fisheries management, fishery closure, income diversification, salmon.

Introduction

Fishers are an integral part of nearly all marine ecosystems. Their behaviour both drives and is driven by changes in the ecosystem, resulting in complex interactions between climate, fishing, harvested populations, and other associated components of the system. The interdependence of fishing, ecology, and climate can be particularly important for upwelling-driven systems where climate fluctuations are strongly linked to population-level processes across many marine species (Doney *et al.*, 2012). The high variability in productivity in these fisheries can motivate fishers to maintain complex fishing portfolios that enable them to adjust to ups and downs in individual fisheries (Kasperski and Holland, 2013), and this has the potential to transmit climate related shocks across species that are not linked ecologically.

The California Current Large Marine Ecosystem (CCLME), reaching from southern British Colombia to Baja Mexico, is a highly productive, variable upwelling system that supports many interlinked fisheries. Basin-scale atmospheric and oceanic processes, particularly the El Niño Southern Oscillation, Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation, and North Pacific High pressure system, influence temperature, wind patterns, circulation, upwelling, and other ocean conditions. These physical conditions in turn influence primary productivity, zooplankton, and higher trophic levels, including fish, birds, and marine mammals through both direct (physiological) and indirect (trophic) effects (Mantua *et al.*, 1997; Di Lorenzo *et al.*, 2008; Schwing *et al.*, 2010; King *et al.*, 2011; Schroeder *et al.*, 2013; Sydeman *et al.*, 2014). The success of many US West Coast fisheries is also tied to biophysical conditions in the CCLME at various spatial and temporal scales. For example, the famous collapse of the lucrative California sardine fishery in the late 1940s has been (at least partially) attributed to the shift from a warm to cool PDO regime across the Pacific (Zwolinski and Demer, 2012).

More recently, in 2008, the collapse of the Sacramento River fall-run Chinook (SRFC; *Oncorhynchus tshawytscha*), in combination with low coho salmon (*Oncorhynchus kisutch*) returns, lead to unprecedented restrictions on salmon fishing along much of the US West Coast, with a complete closure of the ocean Chinook fishery south of Cape Falcon, Oregon and a limited season elsewhere. These restrictions extended into the 2009 season, and resulted in the declaration of a West Coast-wide federal disaster and the release of US $170 million in aid to salmon fishers and other salmon-dependent businesses. The collapse of the SRFC was attributed to poor ocean conditions in 2005 and 2006, with weak upwelling and warm temperatures that resulted in limited prey availability and low survival for the 2004 and 2005 brood years (Lindley *et al.*, 2009). Though the extent of the closure was unprecedented, the collapse was not the first coast-wide salmon disaster tied to poor ocean conditions in recent history, with a federally declared disaster in 1994–1995 attributed to El Niño, drought, flooding, reduced upwelling, and poor ocean conditions. In addition, in 2006 a disaster was declared for the Klamath River basin salmon fishery, where low returns were blamed on poor stream and ocean conditions. Changes in ocean conditions can have a large effect on salmon populations that are already struggling after many decades of reduced and degraded stream habitat. This in turn has serious implications for the salmon fishery. As a mixed stock fishery, the ocean season can be sharply curtailed to protect weaker stocks (many of which are protected under the Endangered Species Act), even when other stocks remain relatively strong.

Anomalous conditions off the West Coast from 2013 to 2015 have raised the possibility of another poor salmon fishing season in 2017 and beyond. The large mass of unusually warm water known as "the Blob" resulted in exceptionally high sea surface temperatures off much of the coast beginning in late 2013 and lasting through 2015 and was associated with greatly reduced upwelling and low productivity in many areas during 2014–2015 (Bond *et al.*, 2015; Peterson *et al.*, 2015a,b). As the Blob faded, the El Niño event of 2015–2016 again brought increased temperatures and decreased upwelling (Jacox *et al.*, 2016). This El Niño is among the strongest in recent history, with the Oceanic Niño Index tying with the previous record set in 1997–1998.

In addition to changes brought by El Niño and the Blob, the PDO changed from negative to positive sign in 2014, indicating a shift to a warmer, lower-productivity phase that is associated with lower salmon returns along the West Coast (Mantua *et al.*, 1997). Together, these ocean conditions have already brought about serious economic consequences for the Dungeness crab, Pacific whiting, market squid, salmon, and pink shrimp fisheries (Peterson *et al.*, 2016). For salmon, these conditions are likely to result in reduced survival of cohorts returning in the next several years (Leising *et al.*, 2015).

Knowledge of the potential impacts of a limited salmon season may aid decision making for managers, fishers, and other stakeholders confronted with the potential of greatly reduced salmon availability, or potential closures, over the next few years. For example, a model of the coho salmon fishery indicated that accurate El Niño forecasts 1–1.5 years in advance of the event could result in up to $1 million in increased revenue (Costello *et al.*, 1998). However, this may greatly underestimate the value of forecasts because it only accounts for the change in direct profits in the fishery resulting from optimizing escapement over time. It does not account for impacts on other fisheries that might be managed better or the potential for fishers to capitalize on advance knowledge of fishery productivity to better utilize their fishing assets and labour.

Predicting the effects of a fishery collapse or closures is complex. The variable strategies and characteristics of individual fishers can result in differing behavioural responses to policy changes and/or altered resource availability (e.g. Zhang and Smith, 2011). This fleet-level heterogeneity may be especially important in fisheries like the West Coast salmon fishery, which includes a wide range of vessel sizes with diverse fishing strategies and involvement in a range of other fisheries. These vessels are unlikely to respond to anomalous events in a uniform manner; thus, it is useful to quantify how the effects of the most recent closure of the fishery varied across vessels, with the goal of identifying the characteristics of vessels that are more vulnerable to the effects of reduced salmon availability. In addition, changes in salmon availability may cause fishers to divert some or all of their effort into alternate fisheries, and this is likely to vary across vessels and depend on which other fisheries they participate in. Such shifts may then affect the profitability and sustainability of other fisheries. Changes in fishing patterns may also affect coastal economies as the revenue brought in by vessels shifts in magnitude, timing, and/or space.

We conduct an analysis of the direct and indirect effects of the 2008–2009 West Coast Salmon fishery closure with the goal of identifying which fishers were affected, how they responded to the closure, and whether there were substantial indirect effects on other fisheries. We develop and apply methods that can be used to predict impact of potential future closures, which can provide fishery managers, participants, and other stakeholders, with an opportunity to prepare and perhaps mitigate impacts. We focus on the behaviour of troll fishing vessels before, during, and after the 2008–2009 closure, with the goal of identifying the characteristics of fishers that are linked to increased vulnerability or resilience to the closure. In addition, we explore whether the salmon troll fleet altered their effort in other fisheries during the closure, and quantify the effects of the closure on port-level revenues. Specifically, we model the vessel-level decision to fish each year as a function of fisher characteristics including revenue level, diversification, dependence on salmon, and spatial descriptors of area and range. We further model relative revenue each year as a function of fisher characteristics, and address whether the closure differentially impacted vessel fishing behaviour and revenue. Because some vessels appear to have exited fishing entirely, we model the vessel-level decision to stay or leave fishing following the closure as a function of vessel characteristics and examine differences between the "stayers" and "leavers". In addition, we examine whether vessels altered their participation in non-salmon fisheries during the closure. Finally, we examine whether relative port-level dependence on salmon was correlated with reduced revenue during the closure.

Methods

Background on the study system

Major fisheries on the US West Coast include salmon, Dungeness crab, whiting, non-whiting groundfish (including flatfish, rockfish, and sablefish), albacore tuna, squid, coastal pelagics, shrimp, and other shellfish. There is a high degree of interdependency among fisheries (including salmon), as they are linked by common environmental and economic factors, as well as by the high degree of overlap in participation. Fishers are thought to move between fisheries across the season according to changes in profitability, species distributions, and regulations. Most fisheries are limited-entry, meaning that fishers must buy an existing license before entering, and many already hold licenses in multiple fisheries. These fisheries are governed by a complex mixture of state and federal management, with a few straddling stocks also covered under international treaties. In Washington, the salmon and steelhead fisheries are co-managed by American Indian tribes who have rights to half of the catch in their usual and accustomed fishing grounds.

Though current salmon runs are only a fraction of their historical sizes, the salmon fishery is one of the more important fisheries on the West Coast, with landings valued at ∼US$35 million during the most recent peak in 2013 (PMFC, 2016). There are five species of Pacific salmon on the US West Coast, each of which is comprised of a number of runs associated with certain freshwater spawning habitats and (for Chinook) spawning migration seasons. Chinook salmon dominate ocean commercial catches, though some coho and small numbers of pink, sockeye, and chum salmon are also taken. Ocean catches are highest in California in most years, followed by Oregon and Washington. Hatchery supplementation is used to enhance production in the face of declining natural stocks, particularly for Chinook and coho. Due to their anadromous life history, both freshwater and marine conditions affect salmon survival, and environmental variability can cause large fluctuations in salmon returns across space and time. The ocean salmon season must be implemented such that it meets escapement and rebuilding goals across runs, and as mentioned earlier the fishery may be highly restricted to protect stocks with low projected returns. The SRFC stock is particularly important for the fishery, historically providing 80–95% of the California ocean harvest (CDFW, 2013) as well as a portion of catches in Oregon. The commercial ocean salmon fishery relies on trolling, while river, sound, and estuarine fisheries use gillnets and purse seines. Well over 1000 fishing vessels participate in West Coast salmon troll fisheries in most years, typically in combination with other fisheries (particularly Dungeness crab, non-whiting groundfish, and albacore tuna). These fisheries are seasonal, meaning that some are complimentary (e.g. the winter Dungeness crab fishery and the summer salmon fishery), and some may be at least partially substitutable (e.g. the summer albacore and salmon fisheries).

Definition of salmon ocean troll fleet

When modelling fishing behaviour and impacts of the closure on the salmon fleet our unit of observation is the fishing vessel. In most cases vessels belong to an owner-operator, though in some cases firms own multiple vessels or vessels are owned by more than one person. Although it might be preferable to model firm or individual behaviour, data availability limits us to modelling vessel behaviour. To define our group of focal vessels (henceforth referred to as the salmon troll fleet), we first identified any commercial vessels that participated in the salmon troll fishery in any capacity from 2001 to 2007 (the year before the closure). Of these vessels, we selected vessels that met the following criteria:

(i) Total annual revenue from salmon troll fishing averaged at least $1000 per year over 2001–2007 (excluding any years when the vessel did not fish).

(ii) Revenue from salmon troll averaged at least 5% of total vessel revenue per year over 2001–2007.

(iii) The vessel fished at least 3 of 7 years in 2001–2007.

Vessels that met these criteria formed a cohort of focal vessels that we followed through time in order to quantify their responses to the closure. All data were taken from the Pacific States Marine Fisheries Commission's PacFin database (PacFin, 2016). Revenues were adjusted for inflation relative to 2005 using the personal consumption expenditure series (http://www.bea.gov/national/consumer_spending.htm). Any revenue from Dungeness crab landed in November and December was grouped with revenue in the next calendar year. This is because the Dungeness season typically runs from mid-November or December through the following spring and summer, and this method of grouping ensures that an entire fishing season is represented in each year.

Fisher/vessel characteristics

To identify vessel characteristics that may modulate the effects of the closure, for each vessel in each year we calculated 5-year moving averages (excluding the current year) of (i) total annual vessel revenue; (ii) percent of revenue from salmon troll; (iii) latitudinal centre of gravity (LCG); (iv) latitudinal inertia (LI); and (iv) Herfindahl-Hirschman index (HHI; Hirschman, 1964). We chose 5-year lagged averages in order to smooth out interannual variation while still identifying vessel characteristics that are likely to affect fishing behaviour in the current year. We did not include years when the vessel did not fish in calculating mean annual revenue.

LCG for a given vessel in a given year is calculated as

$$LCG = \frac{\Sigma_i rev_i \cdot lat_i}{\Sigma_i rev_i} \quad (1)$$

where rev_i is total revenue landed in port i in that year and lat_i is the latitude of that port. This can be thought of as a measure of a vessel's typical landing location along the West Coast. Similarly, we calculated annual latitudinal revenue inertia for each vessel as

$$LI = \frac{\Sigma_i rev_i (lat_i - LCG)^2}{\Sigma_i rev_i} \quad (2)$$

This describes the dispersion around the centre of gravity and can be thought of as a measure of how far a vessel tends to range from its mean landing location.

The HHI, also called the Simpson diversity index, is a measure of income diversification that ranges from near zero to 10 000, with higher values indicating less diversified income sources. It is defined as

$$HHI = \Sigma_j p_j^2 \quad (3)$$

where p_j is the percent of annual revenue from species group j landed by a given vessel in a given year. For details of the species groups used see Kasperski and Holland (2013). In order to facilitate interpretation, in all further analyses we use the inverse HHI (i.e. 1/HHI), such that a higher value indicates higher diversification.

Models of fishing behaviour and revenue

Previous modelling of fishery participation has focused primarily on the decision of when or where to fish conditional on participating in a particular fishery (Eales and Wilen, 1986; Curtis and Hicks, 2000; Hicks and Schnier, 2008; Abbott and Wilen, 2010, 2011; Haynie and Layton, 2010; Zhang and Smith, 2011). A smaller literature has allowed for non-participation within a season (Berman *et al.*, 1997; Smith and Wilen, 2003; Kahui and Alexander, 2008) or longer-term decisions of fishery participation or entry-exit behaviour (Bockstael and Opaluch, 1983; Ward and Sutinen, 1994), but largely in a single-fishery context. These models generally assume participation or location choices are based on the expected revenue in the object fishery and/or location. They do not address the more complex fleet dynamics of West Coast fisheries where fishers may participate in multiple fisheries over the year, and the decisions of which fisheries to participate in—or whether to sit out fishing entirely in a given year—are likely highly interdependent. We are unaware of prior models that address how a closure of one fishery affects decisions of fishers to continue participation in other non-contemporaneous fisheries.

We posit that the decision to continue fishing in other fisheries during the closure year, the fishing revenue generated by vessels that do continue fishing in the closure year, and the decision to permanently exit the fishery, will depend on how much revenue the vessels have been deriving from fishing (including salmon and non-salmon revenues) as well as the share of that revenue coming from salmon (i.e. dependence on salmon). While we do not have information on non-fishing income, we posit that vessels with low overall fishing income are likely to have non-fishery sources of income they may rely on in the event of a closure making their exit from the fishery more likely. We posit that vessels with a range of other fishing opportunities (as measured by their fishery revenue diversification) are more likely to continue fishing in other fisheries during the salmon closure. We also posit that the location of the vessel's previous fishing area will impact fishing behaviour in the closure year since some vessels were able to continue fishing salmon north of the closed area. Finally, we hypothesize that the vessel's spatial range may affect its behaviour and revenue, as more mobile vessels may be more flexible and able to utilize a wider range of fishing grounds.

We took a two-step approach to modelling vessel behaviour and revenue. First, we fit binomial generalized linear mixed models (GLMMs) with a logit link to model the decision to fish each year. GLMMs are hierarchical models that allow for non-normal response variables as well as correlated data (e.g. repeated measures over time of the same individuals). Mixed models where the intercept is allowed to vary randomly across individuals or groups are similar to random-effects panel models used in econometrics, where unobserved individual or group effects are uncorrelated with the regressors. In our case, we hypothesized that the decision to fish in a given year would be influenced by a vessel's characteristics (revenue level, revenue diversification, spatial descriptors, dependence on salmon, and number of years fished in the prior 5 years) as well as constants for the year and whether or not the ocean fishery closure was in effect. In addition, we hypothesized that vessel characteristics may modulate the response of vessels to the closure. Thus, we modelled the probability p_{yi} that vessel i fishes in year y as

$$\begin{aligned}\text{logit}(p_{yi}) = \alpha &+ \beta_1 y + \beta_2 closure + \beta_3 mean.revenue_i \\ &+ \beta_4 mean.HHI_i + \beta_5 mean.percent.troll_i \\ &+ \beta_6 mean.LCG_i + \beta_7 mean.LI_i + \beta_8 years.fished_i \\ &+ \beta_9 closure \cdot mean.revenue_i + \beta_{10} closure \cdot mean.HHI_i \\ &+ \beta_{11} closure \cdot mean.percent.troll_i \\ &+ \beta_{12} closure \cdot mean.LCG_i + \beta_{13} closure \cdot mean.LI_i \\ &+ \beta_{14} closure \cdot years.fished_i + a_i \end{aligned} \tag{4}$$

where *closure* is a dummy variable that takes on a value of 1 during the closure (2008 and 2009) and zero otherwise (In Equation (4) as well as (6–9), note that the variables on the right hand side are constructed with data from the prior 5 years to avoid endogeneity.). We define year as number of years since the first year in the time period we are modelling (2001–2015). The random intercept term a_i is normally distributed. All numerical explanatory variables were centred and scaled by their standard deviation to facilitate model fitting and interpretation (Schielzeth, 2010). We calculated variance inflation factors to assess collinearity in the model and found that all values were <2.5, indicating no concerning collinearity. In addition, we calculated the condition number κ of the design matrix and found $\kappa = 4.6$, again indicating low collinearity. GLMMs were fitted using the package *lme4* (Bates *et al.*, 2015) in R 3.2.3 (R Development Core Team, 2015). Marginal and conditional pseudo-R^2 values were calculated according to Nakagawa and Schielzeth (2013). To assess the predictive power of our model, we used the area under curve (AUC) of the receiver operating characteristic (ROC). This method, which originates in the signal processing literature and is commonly used to assess the fit or predictive power of dichotomous models, has increasingly been used in ecology, medicine, and other fields (Fielding and Bell, 1997). To construct the ROC we used k-fold cross-validation, where we randomly divided the vessels into groups of 100. We trained the model on all but one group, then tested it on the selected group. This was repeated on each group. To evaluate model performance we use the common rule of thumb where AUC ≤ 0.6 is failed, $0.6 <$ AUC ≤ 0.7 is poor, $0.7 <$ AUC ≤ 0.8 is fair, $0.8 <$ AUC ≤ 0.9 is good, and $0.9 <$ AUC ≤ 1.0 is excellent.

For vessels that fished in a given year, we calculated their revenue anomaly z_{yi} as the total revenue of fishing vessel i minus its long-term (2001–2015) mean revenue, scaled by the long-term standard deviation:

$$z_{yi} = \frac{revenue_{yi} - mean.revenue_i}{sd.revenue_i} \tag{5}$$

This serves as a measure of vessel revenue relative to its average revenue over the entire time period. As the second step in our approach, we then model the revenue anomaly as

$$\begin{aligned} z_{yi} = \alpha &+ \beta_1 y + \beta_2 closure + \beta_3 mean.revenue_i + \beta_4 mean.HHI_i \\ &+ \beta_5 mean.percent.troll_i + \beta_6 mean.LCG_i + \beta_7 mean.LI_i \\ &+ \beta_8 years.fished_i + \beta_9 closure \cdot mean.revenue_i \\ &+ \beta_{10} closure \cdot mean.HHI_i + \beta_{11} closure \cdot mean.percent.troll_i \\ &+ \beta_{12} closure \cdot mean.LCG_i + \beta_{13} closure \cdot mean.LI_i \\ &+ \beta_{14} closure \cdot years.fished_i + \epsilon \end{aligned} \tag{6}$$

We use a simple linear model here, as standardizing revenue using each vessel's long-term mean and standard deviation accounts for individual vessel-specific effects. As our primary focus is on the change in revenue during the closure, we excluded vessels that did not fish in 2008 or 2009 from this analysis.

For predictive purposes, we also modelled untransformed annual vessel revenue using the linear model

$$\begin{aligned} revenue_{yi} = \alpha + \beta_1 y + \beta_2 closure + \beta_3 mean.revenue_i \\ + \beta_4 mean.HHI_i + \beta_5 mean.percent.troll_i \\ + \beta_6 mean.LCG_i + \beta_7 mean.LI_i + \beta_8 years.fished_i \\ + \beta_9 closure \cdot mean.revenue_i + \beta_{10} closure \cdot mean.HHI_i \\ + \beta_{11} closure \cdot mean.percent.troll_i \\ + \beta_{12} closure \cdot mean.LCG_i + \beta_{13} closure \cdot mean.LI_i \\ + \beta_{14} closure \cdot years.fished_i + \epsilon \end{aligned} \tag{7}$$

Because diagnostic plots indicated heavy-tailed residuals, we took a robust regression approach using the package *robustbase* (Todorov and Filzmoser, 2009; Rousseeuw *et al.*, 2016).

Stayers and leavers

We hypothesized that the salmon ocean fishery closure may have caused some vessels to exit fishing entirely. To identify vessels that permanently left fishing during 2008–2009, any vessels that did not have any commercial landings in 2008–2015 were classified as "leavers", while vessels that did have commercial landings during this time were classified as "stayers" (Hackett *et al.*, 2015). We then used a binomial generalized linear model (GLM) with a logit link (i.e. a logistic model) to model the decision to leave the fishery and not return following the closure. Thus, we modelled the probability p of staying in the fishery as

$$\begin{aligned} \text{logit}(p) = \alpha + \beta_1 mean.revenue + \beta_2 mean.HHI \\ + \beta_3 mean.percent.troll + \beta_4 mean.LCG + \beta_5 mean.LI \\ + \beta_6 years.fished \end{aligned} \tag{8}$$

where the predictor variables are as defined above.

We also compared the vessel characteristics of stayers and leavers using Wilcoxon-Mann-Whitney tests to determine whether the characteristics of these vessels differed significantly. Specifically, we examined differences in mean revenue, mean HHI, mean centre of gravity, mean inertia, and number of years fished across vessels that remained in the fishery and vessels that left fishing completely during the closure.

Predictions

Unfavourable ocean conditions from 2013 to 2015 suggest that low salmon returns are likely in the next few years. We demonstrate the utility of the models above by predicting the impacts of a potential closure in 2017. To do so, we first identify the current salmon troll fleet using the criteria outlined above. This includes vessels that participated in the salmon troll vessels over the 2009–2015, accounting for vessels that dropped out during the closure and vessels that entered during or since the closure. We then predict the proportion of vessels that will not fish, and the revenue of those that remain. For the binomial models, we chose cutoff values that maximized the sum of the model sensitivity and specificity. For simplicity, we assume that the extent and location of the closure is the same as that in 2008. We also compare mean vessel characteristics of the current fleet to characteristics of the pre-closure fleet in order to identify any changes in overall fleet characteristics that may influence responses to a closure.

Port-level analyses

Reductions in fishing revenue are likely to resonate across fishing communities, but the responses may differ across locations. To identify the dependence of individual ports on revenue from salmon troll vessels, we calculated the mean proportion of annual revenue from salmon troll vessels prior to the closure (2001–2007) for each port. Then, in each year we calculated the port-level revenue anomaly analogously to the vessel-level anomaly described above, using mean and standard deviation of total annual revenue landed in each port over 2001–2015. We then regressed port dependence on salmon troll vessels against port revenue anomaly in each year to determine if ports that were more dependent on salmon tended to have lower revenue during the closure.

Participation in other fisheries

We hypothesized that in years when salmon availability is limited, vessels that participate in the salmon fishery may shift some of their effort into other fisheries. This is based on the observation that most of our focal vessels participate in multiple fisheries, meaning they could potentially attempt to make up for lost salmon revenue by increasing effort in other fisheries. To explore whether vessels in the salmon troll fleet altered their participation in other fisheries during the salmon troll closure, we first identified vessels that participated in the groundfish, crab, and/or highly migratory species (HMS, mainly albacore tuna) fisheries in the 7 years preceding the closure. This was done to identify boats that likely had the ability (in terms of gear, expertise, and permits) to participate in those fisheries during the closure. We chose these three fisheries because they represent the main non-salmon fisheries that our focal fleet participates in. We then constructed a set of binomial GLMMs to examine the probability a vessel (within the subset of the fleet identified above) participates in each of these fisheries each year, given that it chooses to fish at all. The probability p that vessel i participates in a given fishery in year y is

$$\begin{aligned} \text{logit}(p_{yi}) = \alpha + \beta_1 y + \beta_2 closure + \beta_3 mean.revenue_i \\ + \beta_4 mean.HHI_i + \beta_5 mean.percent.troll_i + \beta_6 area_i \\ + \beta_7 mean.LI_i + \beta_8 years.fished_i \\ + \beta_9 closure \cdot mean.revenue_i + \beta_{10} closure \cdot mean.HHI_i \\ + \beta_{11} closure \cdot mean.percent.troll_i + \beta_{12} closure \cdot area_i \\ + \beta_{13} closure \cdot mean.LI_i + \beta_{14} closure \cdot years.fished_i + a_i \end{aligned} \tag{9}$$

Here the predictor variables are the same as the variables in the salmon fishery participation model, with the exception of *area*. This is a categorical value representing the location of the vessel's mean centre of gravity (southern California, northern California, Oregon, or Washington) and was chosen to characterize typical vessel location while avoiding model convergence issues. Northern and southern California were defined as the areas within California north and south of Pt. Arena (39°N), respectively.

In addition to the models above, we also examined total effort in other fisheries across all vessels in the fleet. This is important because the impact on other fisheries is likely mostly driven by the total change in effort across the fleet, regardless of changes in individual behaviour. To do so, we constructed time series of total number of trips undertaken by our focal fleet in the crab, groundfish, and HMS fisheries. We then used the method of Chen and Liu (1993) to detect outliers in these time series that might correspond to shifts in effort that occurred during the closure. This method identifies four different kinds of outliers (additive outliers, innovation outliers, level shifts, and temporary changes) in autoregressive moving average (ARMA) time series models. This was implemented using the package *tsoutliers* version 0.6 (López-de-Lacalle, 2015). In order to disentangle the potential effects of reduced participation during the closure (i.e. the fact that fewer boats overall participated in fishing), we also performed this analysis on the subset of vessels that fished at least 1 year in 2008 and 2009.

We also hypothesized that the salmon closure may have altered the fleet-level seasonal distribution of effort across fisheries. That is, if vessels cannot fish for salmon during their usual season, they may fish for other species during that time, altering the intra-annual pattern of participation in that fishery. To test this hypothesis, we created monthly time series of the number of trips undertaken in each fishery (crab, groundfish, HMS, and salmon) and calculated the monthly share of total annual trips for each month. We then constructed seasonal dummy regressions where share of trips s taken in a fishery is

$$s_{month} = \alpha + \beta \cdot month + \epsilon \quad (10)$$

where *month* is a dummy variable. We then tested for structural change in these regressions using both the supF test (which tests for a single unknown breakpoint using F-statistics; Andrews, 1993) and the Bai–Perron test (Bai and Perron, 1998, 2003), which tests for the presence of multiple unknown breakpoints using the Bayesian information criterion and the residual sum of squares. These analyses were done using the *strucchange* package in R (Zeileis *et al.*, 2002).

Results

Characteristics of the focal vessels

We identified 1214 vessels that met the criteria for belonging to the salmon troll fishery prior to the closure, forming our focal group of vessels. In a given year, the number of these vessels participating in fishing of any kind ranged from a high of 1141 in 2004 to a low of 691 in 2009, not including any new entrants during or after the closure (Figure 1). These vessels were quite diverse with wide ranges of annual revenue and varying portfolios of target fisheries. Mean total annual per-vessel revenue from 2001–2015 ranged from \$610 to \$549 881, with a median of \$24 273 (excluding years in which vessels did not fish; Figure 2). On average, vessels obtained 55% of their annual revenue from salmon, ranging from 2 to 100% (Figure 2). Other fisheries that these vessels participated in include groundfish (particularly sablefish), crab (almost exclusively Dungeness crab), and HMS (mainly albacore). A smaller number of vessels targeted shrimp (mainly spotted prawns and pink shrimp), coastal pelagics (mainly market squid and Pacific herring), or other species (e.g. halibut, hagfish, white seabass, and California spiny lobster). Mean vessel inverse HHI values indicated that most vessels were somewhat diversified, but 77 vessels fished salmon exclusively over this time period, giving them the minimum mean inverse HHI of 0.0001 (Figure 2). The distribution of vessel centres of gravity indicates that these vessels tend to be concentrated in central-north California, northern Oregon, and to a lesser extent northern Washington. Mean inertia values were generally low (median = 0.08), indicating that most vessels did not range very far from their centre of gravity. Vessels fished a median of 12 years during 2001–2015 (Figure 2).

Total annual revenue from these vessels combined ranged from US\$31 583 026 in 2009 to US\$73 289 081 in 2012. Total revenue in 2008 was US\$35 432 584 while the average annual revenue in the 5 years before the closure was US\$56 200 864, indicating that the closure was associated with a reduction of US\$45 386,118 in total revenue during the 2-year period relative to the preceding time period. Mean annual revenue from salmon troll among these vessels was US\$19 041 815 in 2003–2007, compared with US\$1 473 554 in 2008 and US\$1 777 552 in 2008, indicating a loss of US\$34 832 524 in salmon troll revenue during 2008–2009.

Crab and salmon brought in the most revenue to these vessels, followed by groundfish and HMS, with relatively small overall contributions from coastal pelagics, shellfish, shrimp, and other groups (though these were important sources of revenue for a small number of individual vessels). Crab revenue was relatively low during the closure, likely due to natural fluctuations in crab abundance (Figure 3).

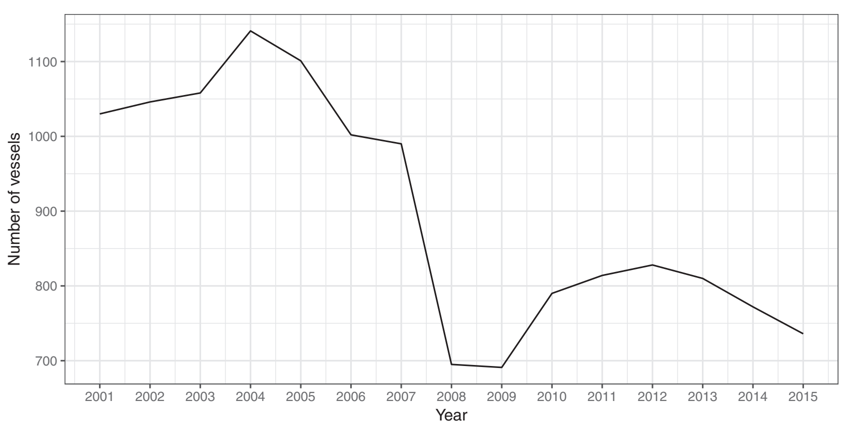

Figure 1. Number of focal salmon troll vessels that participated in fishing each year.

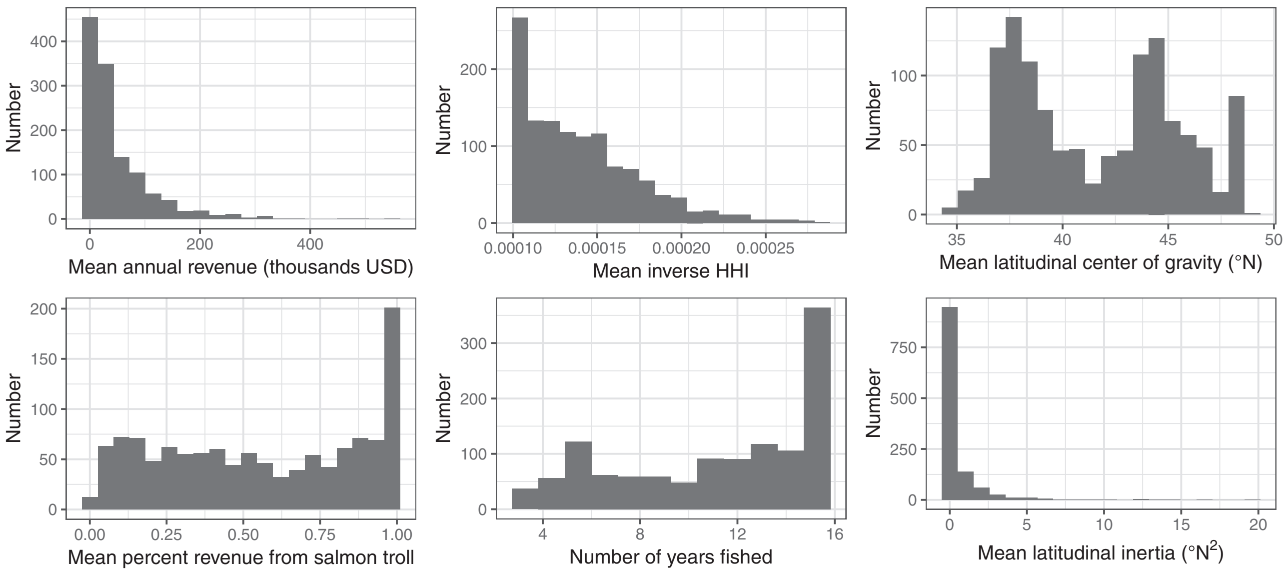

Figure 2. Histograms of vessel characteristics averaged across 2001–2015.

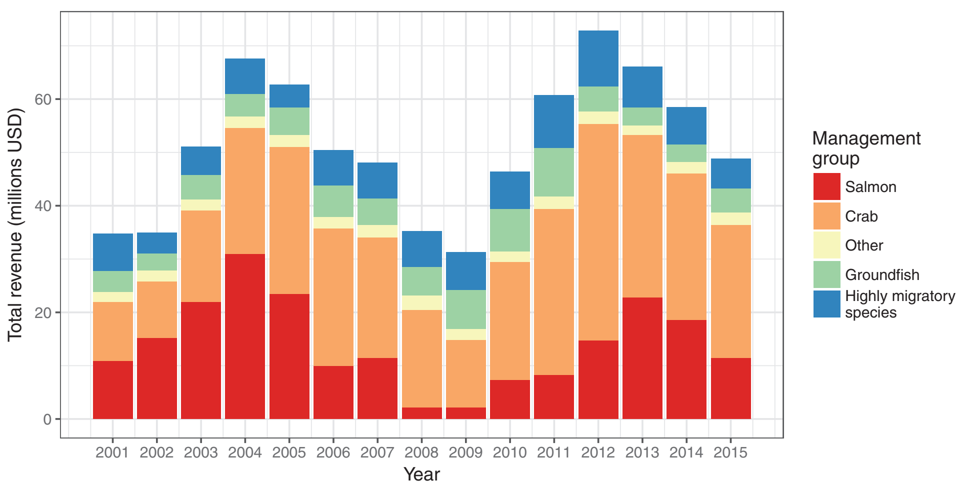

Figure 3. Total annual revenue from each management group harvested by vessels in the salmon troll fleet.

Binomial fishing behaviour model

The binomial GLMM indicated that all predictors were significant at the $p = 0.05$ level, with the exception of inertia and the main effect of percent of revenue from salmon troll. We did not drop inertia from the model as doing so resulted in slightly higher Akaike information criterion value (11521.1 vs. 11519.2). The marginal pseudo-R^2 was 0.45 and the conditional pseudo-R^2 was 0.62, suggesting that the model fixed effects explained ~45% of the variance while the fixed and random effects together explained ~62%. The AUC was 0.84, demonstrating good model fit. Year, closure, and centre of gravity all had significantly negative main effects, indicating that they decreased the probability a vessel fished in a given year. Revenue, diversification (inverse HHI), and the number of years fished in the past 5 years had significant positive effects (Supplementary Table S1; Figure 4a). The interaction between closure and revenue was negative, indicating that the positive effect of revenue was lessened during the closure. The interaction between closure and percent of revenue from salmon troll was also negative, suggesting that vessels more dependent on salmon troll revenue were less likely to fish during the closure years, though this vessel characteristic has no significant impact outside of the closure. The interaction between closure and diversification was positive, demonstrating that more diversified vessels were relatively more likely to fish during the closure years. The effect of number of years fished was also more positive during the closure years. Though the main effect of centre of gravity was negative, the interaction of closure and centre of gravity was positive, indicating that the closure affected vessels differentially across space, with more northern vessels more likely to fish during the closure years. Overall, vessel revenue, the presence of a closure, and the interaction between closure and vessel dependence on salmon troll had the largest effects, suggesting they have the greatest impact on whether or not a vessel fishes in a given year.

Revenue models

Relative vessel revenue varied greatly across years, with the lowest median anomalies occurring during the closure (Figure 5).

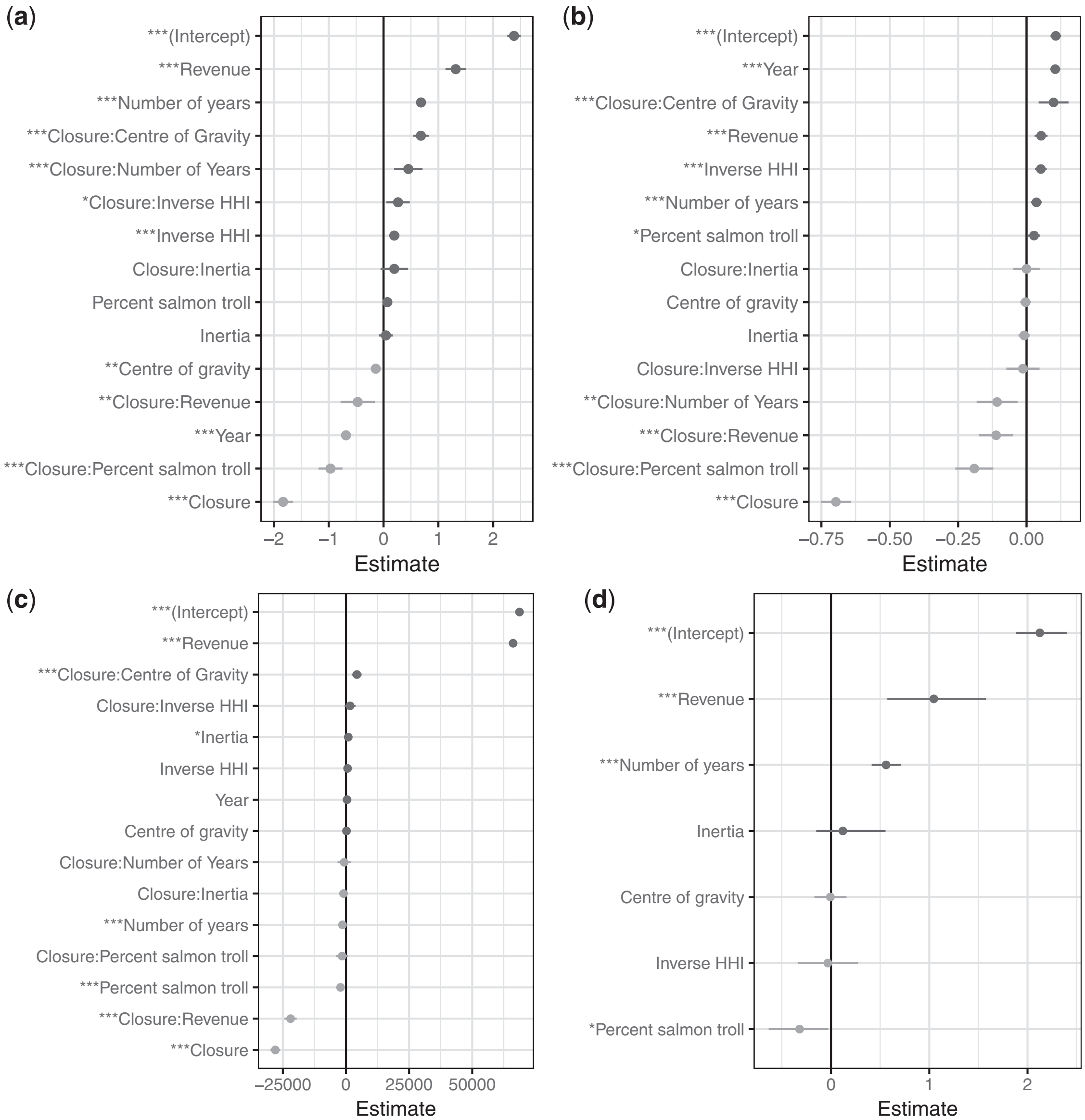

Figure 4. Coefficient estimates from models of (a) annual fishing participation; (b) revenue anomaly; (c) untransformed revenue; (d) decision to stay in fishing following the closure. Horizontal bars represent 95% CIs. Asterisks represent *p*-values (***$p < 0.001$, **$p < 0.01$, *$p < 0.05$).

During these years, 82–83% of vessels had negative revenue anomalies, indicating that the large majority of vessels that fished in the closure years made less money than average. However, though our model identified significant predictors of vessel revenue anomaly (Supplementary Table S2; Figure 4b), overall fit was poor, with $R^2 = 0.09$. The presence of the closure had the largest effect on revenue anomaly, and significantly negative interactions with closure indicate that vessels with higher revenue, greater dependence on salmon, and more years fished saw greater declines in relative revenue during the closure.

The model of untransformed revenue had better fit, with $R^2 = 0.75$. Unsurprisingly, mean revenue over the past 5 years was the strongest predictor of annual vessel revenue (Supplementary Table S3; Figure 4c). The closure was associated with a significantly negative effect on revenue, as was the interaction between closure and mean revenue.

Stayers and leavers

We found that 209 vessels exited fishing completely during the closure, representing ∼17% of the fleet. The GLM of the probability of remaining in the fishery suggested that vessels with higher revenue and a greater number of years fished were more likely to stay, while vessels that had a higher proportion of revenue from salmon troll were more likely to exit (Supplementary Table S4; Figure 4d). AUC was 0.79, indicating fair model fit.

Though the model did not identify diversification or inertia as significant predictors, we found that on average, leavers were significantly less diverse and had lower inertia than stayers (Table 1). Leavers also tended to have lower mean revenue, a higher proportion of revenue from salmon troll, and fewer years fished. Diversification is positively correlated with average revenues, which could increase the standard error and reduce significance

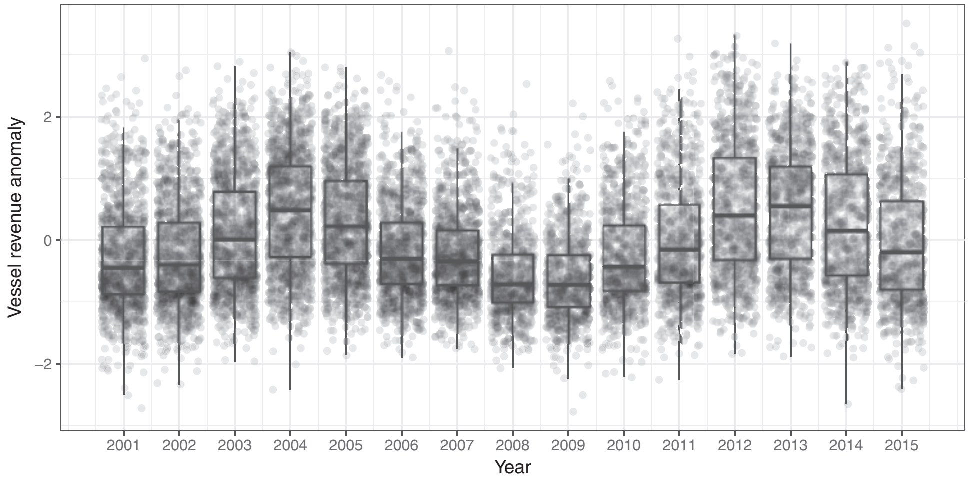

Figure 5. Annual vessel revenue anomaly. Points represent individual vessel values, while boxplots show the quartiles.

Table 1. Average characteristics of stayers and leavers and results from Wilcoxon-Mann-Whitney tests.

Vessel characteristic	Mean stayer value	Mean leaver value	*p* value
Number of years fished	4.54	3.74	**<0.001**
Mean percent salmon troll	0.59	0.82	**<0.001**
Mean revenue	53 541.65	16 630.56	**<0.001**
Mean centre of gravity	41.60	41.36	0.36
Mean inertia	0.74	0.29	**<0.001**
Mean inverse HHI	0.000148	0.000124	**<0.001**

Table 2. Mean vessel characteristics of the pre- and post-closure fleets and results from Wilcoxon-Mann-Whitney tests.

Vessel characteristic	Mean 2001–2007 fleet	Mean 2009–2015 fleet	*p* value
Mean revenue	45 268	43 253	0.107
Mean inverse HHI	0.0001412	0.0001403	**0.020**
Mean percent salmon troll	0.532	0.486	**<0.001**
Mean centre of gravity	41.55	41.59	0.32
Mean inertia	0.6302	0.6319	**<0.001**
Number of years	3.831	3.410	**<0.001**

of this variable. Centre of gravity was not significantly different between stayers and leavers.

Current fleet and predictions

We identified 1089 vessels belonging to the current salmon troll fleet, indicating that the current fleet is $\sim$10% smaller than the pre-closure fleet. This accounts for the 209 vessels that exited fishing entirely, as well as 297 vessels that continued fishing but no longer met our criteria for being salmon troll vessels. It also includes 391 vessels that entered the salmon troll fleet from 2008 onwards. On average, the newer fleet is less dependent on salmon but also slightly less diverse (Table 2). Though mean centre of gravity does not differ, the newer fleet has greater inertia, suggesting more movement across space. Vessels in the new fleet fished fewer years, but this may be driven by new entrants that have a short fishing history. We show the average characteristics of the new entrants in Table 3.

Our model predicts that in the event of another closure, only $\sim$47% of vessels in the current fleet would fish at all during that year (Figure 6). Of the vessels that we predict would fish, our models predict a mean annual revenue of \$65 750 (five vessels were predicted to have negative revenue, so we did not include these vessels in further calculations). In contrast, if there is no closure, we predict that 82% of vessels would fish, and that the average vessel would make \$71 154. Overall, the fleet is predicted to have total annual revenue of \$63 825 400 without a closure and \$33 466 993 with a closure, suggesting a loss of over \$30 million in a single year (Figure 6). Assuming the magnitude of the closure would be similar to the last closure, our model predicts that 303 vessels would exit fishing completely, representing nearly 30% of the fleet.

Table 3. Mean vessel characteristics of new entrants.

Vessel characteristic	Mean
Mean revenue	40 671
Mean inverse HHI	0.0001347
Mean percent salmon troll	0.447
Mean centre of gravity	42.11
Mean inertia	0.4905
Number of years	3.085

Port level analyses

Regressions of importance of the salmon troll fleet to ports (i.e. mean proportion of total annual fishery revenue from salmon troll vessels) against port revenue anomaly were non-significant in all years except 2008–2010 (negative relationship) and 2015 (positive relationship; Figure 7). This indicates that ports that gained more revenue from salmon troll vessels had significantly lower revenue during the closure, and that this effect persisted into the year after the closure. These ports tended to be in central California, northern California, and Oregon. However, these relationships are noisy; indicating that dependence on salmon only

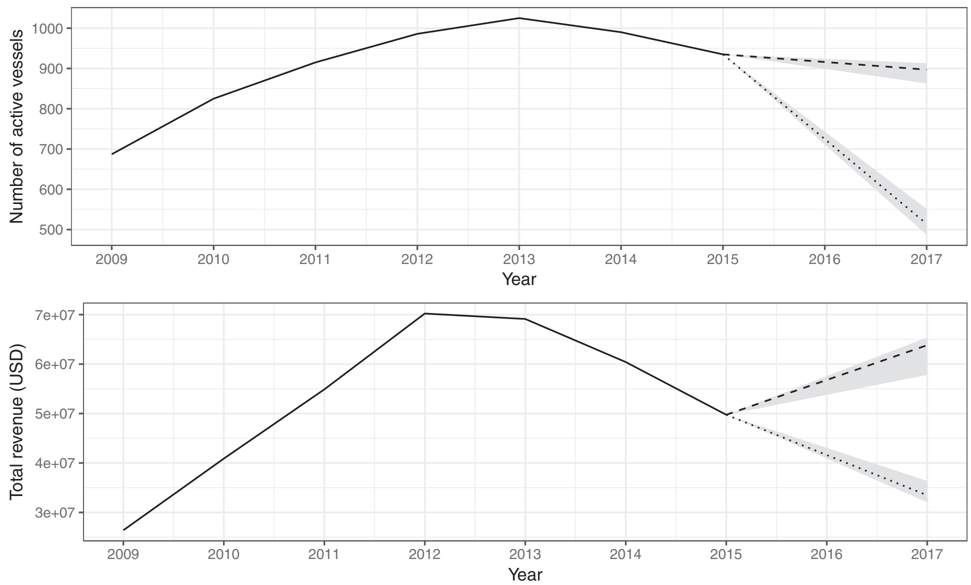

Figure 6. Time series of actual and predicted number of vessels (top) and total revenue (bottom). Solid lines represent actual values, dashed lines are predicted values in the absence of a closure, and dotted lines are predicted values in the presence of a closure. Grey bands are bootstrapped 95% prediction intervals.

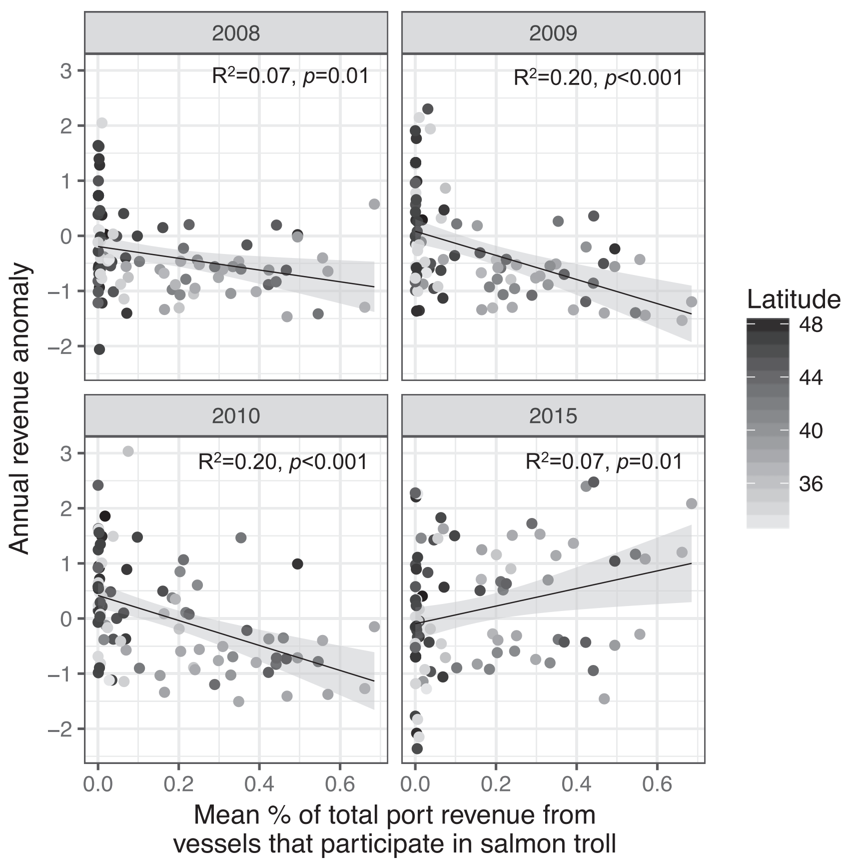

Figure 7. Regressions of mean percent of port revenue from salmon troll vessels versus revenue anomaly. Only years with significant relationships are shown.

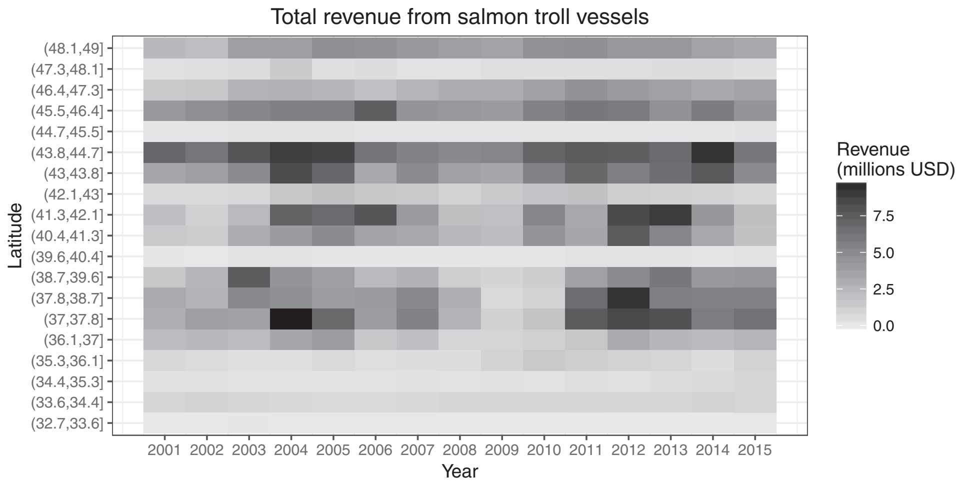

Figure 8. Total revenue from salmon troll vessels across time and latitude.

Figure 9. Proportion of subfleets that participate in major alternate fisheries.

drives part of the fluctuations in port-level revenue. Total revenue across time and latitude is shown in Figure 8.

Participation in other fisheries

Within the salmon fleet, we identified 496 vessels that participated in the crab fishery, 378 vessels that participated in the groundfish fishery, and 428 vessels that participated in the HMS fishery prior to the closure. The proportion of each of these subfleets participating in each fishery annually is show in Figure 9 (proportion of the entire fleet participating in the salmon fishery is shown for comparison). Our models indicated that vessels were significantly more likely to participate in the crab fishery during the closure, though this effect was modulated for Oregon and Washington vessels (Supplementary Table S5; Figure 10a). Our model also suggested that vessels with a lower inertia were more likely to harvest crab during the closure. There was little evidence that the closure increased participation in the groundfish (Supplementary Table S6; Figure 10b) or HMS fisheries (Supplementary Table S7; Figure 10c), though there was some indication that more diversified vessels were less likely to harvest groundfish during the closure. In addition, there was some suggestion that northern California and Oregon vessels, as well as high inertia vessels were more likely to harvest HMS during the closure, but these effects were not statistically significant.

Analysis of total fleet-wide trips in the crab, groundfish, and HMS fisheries did not identify any outliers in each of these time series (Figure 11). This was true even if we extended our time series back to 1995, and if we limited the vessels to those that fished during the closure. This indicates that there was little overall change in effort (in terms of number of trips) in other fisheries over 2001–2015, in spite of a significant proportion of vessels exiting temporarily during the closure and/or permanently following the closure. In contrast, analysis of the fleet-wide number of salmon trips identified a level shift in 2006 and a temporary change in 2008. Extending the time series to 1995 resulted in the additional identification of temporary change in 2004 and an additive outlier in 2007 (Supplementary Figure S1).

In the seasonal time series of fleet-wide proportion of trips, F-statistics suggest a structural change in the seasonality of groundfish trips between 2003 and 2006 (with the sup-F test

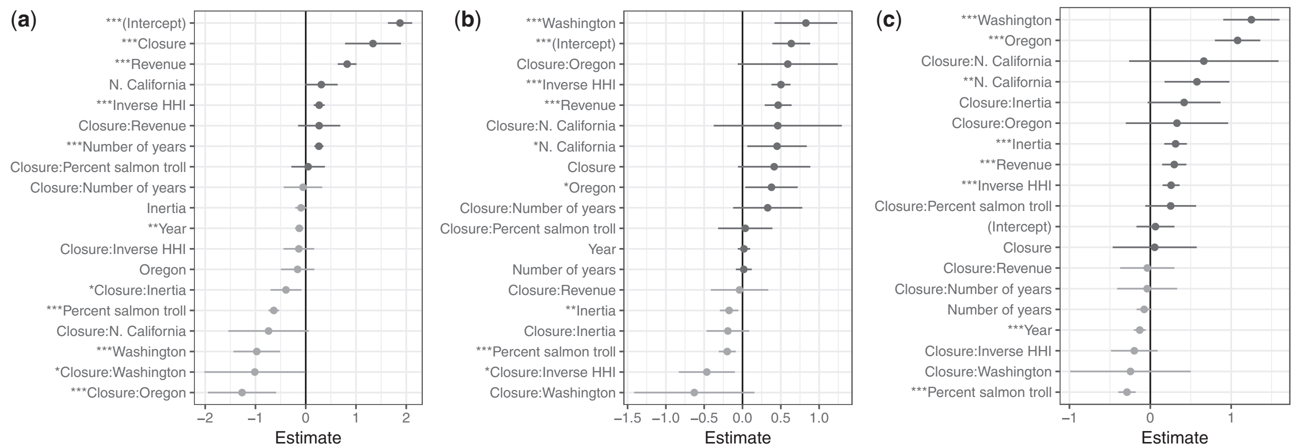

Figure 10. Coefficients from model of participation in the (a) crab fishery; (b) groundfish fishery; and (c) HMS fishery. Horizontal bars represent 95% CIs. Asterisks represent p-values (***$p < 0.001$; **$p < 0.01$; *$p < 0.05$).

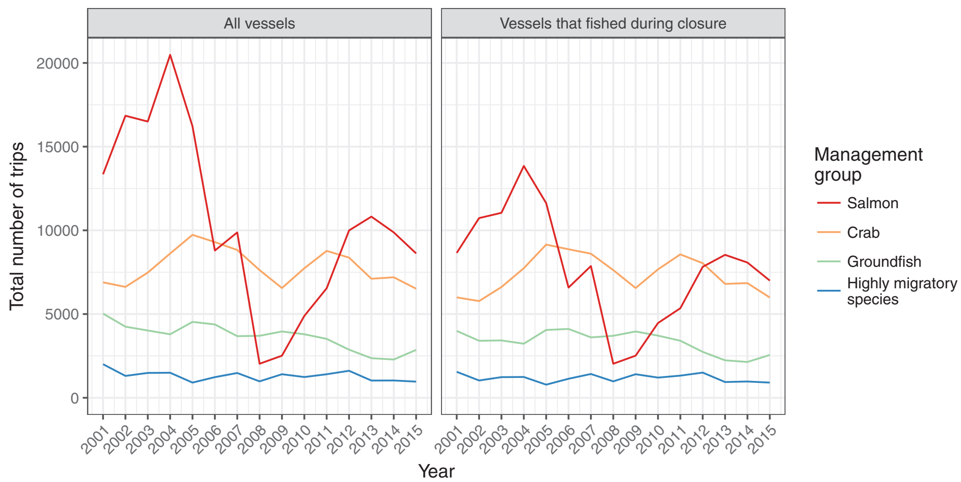

Figure 11. Time series of number of trips in the main fisheries targeted by the salmon troll fleet. Left panel shows trips from all vessels and right panel shows trips by vessels that fished during the closure.

identifying the breakpoint at June 2003), and of salmon trips around 2007 and 2009–2010 (with the sup-F test identifying the breakpoint at May 2010; Figure 12, Supplementary Figure S2). The Bai and Perron method did not identify any breakpoints in the groundfish seasonal time series, but again found support for a structural change in salmon trip seasonality in May 2010 (Figure 12; Supplementary Figure S3). Neither method found evidence of structural changes in crab or HMS trip seasonality. Thus, there is little evidence that the salmon fishery closure altered the intra-seasonal allocation of effort in other fisheries, though it may have impacted the seasonality of the salmon fishery itself.

Discussion

As the earth's climate continues to change, oceanographic variability is likely to have increasing impacts on marine ecosystems. Changes in ocean conditions that alter productivity of particular fisheries can alter behaviour of fishers affecting their harvest, not only of the species directly impacted by oceanic changes, but other species they target. Fishery closures or collapses may have impacts that persist long after the fishery recovers. Anticipating and effectively responding to oceanic variability thus requires understanding whether and how fishers will react to changes by altering their harvesting activities in and beyond directly impacted fisheries, and in the short and long term.

We analysed the 2008–2009 salmon ocean troll fishery closure to quantify how a large fluctuation in resource availability may affect salmon fishers, other fisheries, and fishing communities. Our results indicate that most salmon fishers in the California Current typically have limited alternatives in the face of sharply reduced salmon availability, and this is particularly true for vessels with low revenue diversification. Fishing vessels that are highly dependent on salmon are likely to cease fishing (some permanently) rather than attempting to move into other fisheries. This may be because of difficulty obtaining permits, the cost of retrofitting boats for other fisheries, and/or because fishers gain personal satisfaction from salmon fishing that they would not find elsewhere. The vessels that exited fishing permanently tended to be more dependent on salmon, less diversified, and lower revenue, indicating that these types of vessels may be less resilient to a closure or decline in salmon availability.

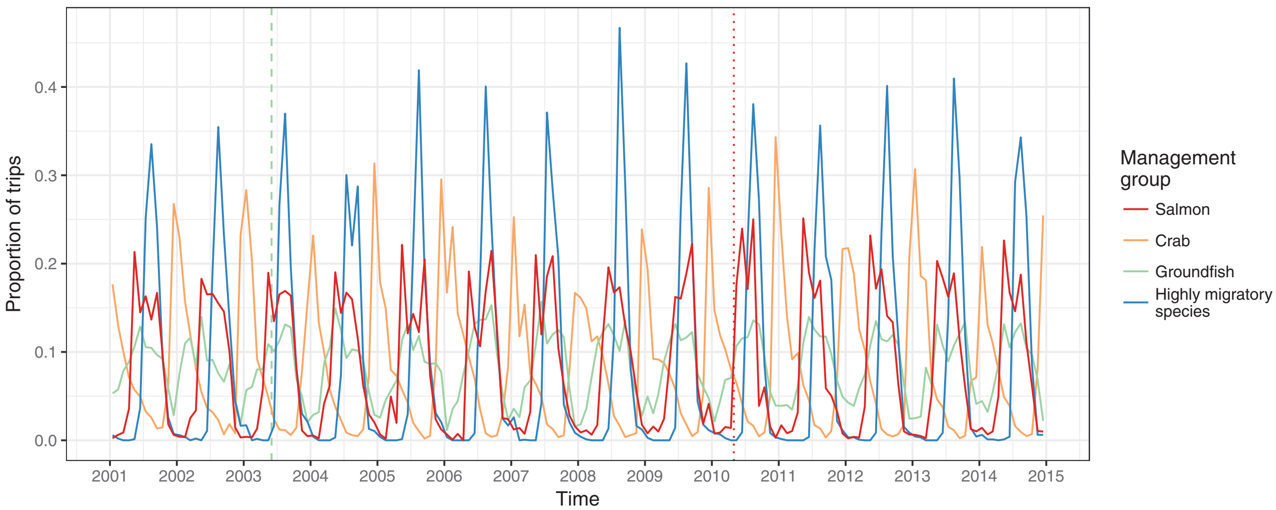

Figure 12. Proportion of total annual trips taken in each month in each management group. Dashed line shows the breakpoint in the groundfish time series identified by the sup-F test and dotted line shows the breakpoint in the salmon time series identified by both the sup-F test and Bai–Perron test.

Vessels that participate in multiple fisheries are more likely to remain active during a salmon fishery closure, albeit often with lower revenue relative to average levels. Though diversification was positively associated with being active in fishing during the closure, we found only limited evidence that these vessels increased their participation in other fisheries. There is evidence that those who previously fished for Dungeness crab were more likely to do so, though the net change in overall effort in the crab fishery resulting from this was probably not large. Dungeness crab recruitment and landings (which are tightly linked to the size of fishable crab population) can fluctuate by an order of magnitude across years due environmental conditions (Shanks, 2013), and crab catches were relatively low in 2008–2009. Low catch rates in the crab fishery may have reduced the degree to which fishers affected by the salmon closure participated in the crab fishery.

The limited displacement of effort into other fisheries during the salmon fishery closure may also partly stem from the complimentary nature of the fishing portfolios often targeted by fishers. For example, while the ocean salmon fishery peaks in the summer, the crab fishery usually opens in December and the majority of catches are usually landed in the first 4–6 weeks of the season, meaning there is little temporal overlap in these fisheries. The groundfish fishery peaks in the summer; however, bimonthly catch limits (for the limited entry fishery) and daily/weekly trip limits (for the open-access fishery) may have limited the ability of vessels to increase their groundfish landings to compensate for the lack of salmon. The albacore fishery peaks in the late summer/early fall, but vessels (particularly smaller vessels) may be limited by weather, hold size, and range, as well as the varying migration patterns of albacore (Dotson, 1980). Access to most West Coast fisheries is also restricted to a limited number of license holders, so fishers cannot freely enter them unless they already have a license or can purchase an existing license from another vessel. Consequently, though many fishers have relatively diversified fishing portfolios, they may already be maximizing their investment in other available fisheries, and have few feasible fishing alternatives during the salmon season. This is supported by our results finding no abrupt changes in the seasonal pattern of trips in the groundfish, crab, and HMS fisheries during 2008–2009. This is also supported at least anecdotally by fishers; for example, one who was interviewed by Ackerman *et al.* (2016) said in reference to the salmon closures,

> The impact for that was tremendous, in that you have communities, for example Garibaldi, where the fisherman, who depend on salmon fishing as part of their fisheries income could not go fishing. If you take away one of those income streams then it's not like you can create more by increasing your catch with albacore or crab.

Thus, though most salmon fishers also participate in other fisheries, those fisheries appear to provide a limited buffer against the effects of poor or no salmon fishing. For vessels that remain in the fishery, the primary strategy in the face of a poor season may be to wait it out, rather than attempt to greatly alter their investment in other fisheries.

The adaptive strategies available to fishers are not limited to their allocation of effort across fisheries. Many of the vessels included in this analysis are relatively low-revenue vessels belonging to small independent owner–operators, and many of these fishers likely have alternate sources of income outside of fishing. This may allow them to cease fishing when conditions are poor, and/or to supplement their fishing income during bad years. However, we currently lack data to quantify these alternate forms of employment and their potential effects on fishing behaviour. Future planned work includes surveys of fishers to gather information about employment outside of fishing, non-monetary benefits of fishing, and other factors that may influence fishing behaviour. This will provide a more complete picture of the factors motivating behaviour and allow us to create more robust models of movement between multiple fisheries, as well as other sectors.

Although this study indicated fairly limited indirect impacts on other fisheries resulting from effort displacement following the salmon fishery closure, the same may not be true for other fisheries subject to impacts of climate variation. For example, in 2015–2016 there was a delay of the California Dungeness crab fishery due to high levels of domoic acid resulting from a harmful algal bloom (HAB) that has been attributed to the Blob (McKibben *et al.*, 2017). Total California crab landings in the 2015–2016 season were down about 50% from the prior year, and there were reports that many crab fishers shifted their effort into the daily trip limit sablefish fishery, resulting in an in-season action by the Pacific Fishery Management Council to lower trip limits to avoid an early closure of the fishery. Researchers and policymakers should explore the behaviour of participants in this and other fisheries that are affected by environmental changes. Responses and effort displacement into other fisheries may differ from what we observed with the salmon closure.

Though we focus our analyses on the closure of 2008–2009, crises in the West Coast salmon fishery have been occurring for the past several decades, including a partial closure in Oregon in 2006. As a consequence of that event, as well as a relatively poor season in 2007, much of the salmon fishery was already struggling when the unprecedented closure of 2008–2009 came about. The coupled marine and terrestrial environments associated with the California Current have already become increasingly variable over the past decades (Black *et al.*, 2014), and future events are likely to include more poor salmon periods of varying spatial and temporal extents. While our analyses focus on the particular events of 2008–2009, we believe that the general patterns we identified are likely to apply to future scenarios, including perhaps the next few years. The methods used in this study should also be generalizable to other fisheries subject to fishery closures associated low productivity or periodic events such HABs.

The results of this study are especially timely as the changes brought by drought, El Niño, the Blob, and the switch to a positive PDO indicate poor conditions for salmon returning in 2016–2018. If there is another closure of similar magnitude (as it appears there will be in 2017), our results suggest that the current salmon troll fleet is likely to face similar consequences. This would mean a large portion of the fleet would cease fishing temporarily, and some would likely leave fishing permanently, with large implications for the fishery and associated industries and communities. However, there is little to suggest that salmon fishers would greatly increase their effort in other fisheries, meaning that direct impacts on the crab, groundfish, and HMS fisheries are likely to be relatively low. It is worth noting that the anomalous environmental conditions over the past few years could lead to negative impacts on fisheries that persist longer than the 2-year closure we focus on in this study. More productive ocean conditions may not return until late 2017 or 2018 (Peterson *et al.*, 2016) meaning salmon returns are not likely to improve for several years following that. Though many fishers in this study were able to survive a 2-year closure, a longer period of highly restricted fishing may cause more attrition and/or movement to other fisheries. Fishers may also need to develop new adaptive strategies, such as diversifying their fishing and non-fishing revenue streams.

In the longer term, changes in climate, stream, and oceanographic conditions may mean that highly restricted salmon seasons may become more common, and other species may face similar changes. As noted earlier, the Blob was associated unprecedented delays in the crab season, as well as negative impacts on other ocean fisheries. The conditions brought by the Blob have been suggested to foreshadow future conditions in the Pacific, with serious consequences for the CCLME and the livelihoods that depend on it. Managers and policymakers may want to consider how fishers are likely to respond to these events, and how policy changes could potentially mitigate some of the unwanted impacts. For example, policymakers might weigh the benefits of facilitating movement among substitute fisheries with the potential impacts on those fisheries and the wider ecosystem. Though a closure may only last 1–2 years, ecosystem and economic effects may persist over much longer time periods, necessitating careful consideration of trade-offs among management options.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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References

Andrews, D. W. K. 1993. Tests for parameter instability and structural change with unknown change point. Econometrica, 61: 821–856.

Abbott, J. K., and Wilen, J. E. 2010. Voluntary cooperation in the commons? Evaluating the Sea State program with reduced form and structural models. Land Economics, 86: 131–154.

Abbott, J. K., and Wilen, J. E. 2011. Dissecting the tragedy: a spatial model of behavior in the commons. Journal of Environmental Economics and Management, 62: 386–401.

Ackerman, R., Neuenfeldt, R., Eggermont, T., Burbidge, M., Lehrman, J., Wells, N., Chen, X. 2016. Resilience of Oregon Coastal Communities in Response to External Stressors. Master's Thesis, University of Michigan, Ann Arbor, Michigan.

Bai, J., and Perron, P. 1998. Estimating and testing linear models with multiple structural changes. Econometrica, 66: 47–78.

Bai, J., and Perron, P. 2003. Computation and analysis of multiple structural change models. Journal of Applied Econometrics, 18: 1–22.

Bates, D., Mächler, M., Bolker, B., and Walker, S. 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67: 48.

Berman, M., Haley, S., and Kim, H. 1997. Estimating net benefits of reallocation: discrete choice models of sport and commercial fishing. Marine Resource Economics, 12: 307–327.

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

Bockstael, N. E., and Opaluch, J. J. 1983. Discrete modelling of supply response under uncertainty: the case of the fishery. Journal of Environmental Economics and Management, 10: 125–137.

Bond, N. A., Cronin, M. F., Freeland, H., and Mantua, N. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters, 42: 3414–3420.

CDFW (California Department of Fish and Wildlife). 2013. Status of the fisheries report: an update through 2011. Report to the California Fish and Game Commission as directed by the Marine Life Management Act of 1998.

Chen, C., and Liu, L.-M. 1993. Joint estimation of model parameters and outlier effects in time series. Journal of the American Statistical Association, 88: 284–297.

Costello, C. J., Adams, R. M., and Polasky, S. 1998. The value of El Niño forecasts in the management of salmon: a stochastic dynamic assessment. American Journal of Agricultural Economics, 80: 765–777.

Curtis, R., and Hicks, R. L. 2000. The cost of sea turtle preservation: the case of Hawaii's pelagic longliners. American Journal of Agricultural Economics, 82: 1191–1197.

Di Lorenzo, E., Schneider, N., Cobb, K., Franks, P., Chhak, K., Miller, A., McWilliams, J. *et al.* 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophysical Research Letters, 35: L08607.

Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., Galindo, H. M. *et al.* 2012. Climate change impacts on marine ecosystems. Marine Science, 4: 11–37.

Dotson, R. C. 1980. Fishing methods and equipment of the US West Coast albacore fleet. NOAA-NMFS Technical Memorandum NOAA-TM-NMFS-SWFC-8.

Eales, J., and Wilen, J. E. 1986. An examination of fishing location choice in the pink shrimp fishery. Marine Resource Economics, 2: 331–351.

Fielding, A. H., and Bell, J. F. 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environmental Conservation, 24: 38–49.

Hackett, S., Pitchon, A., and Hansen, D. 2015. Economic attributes of stayers and leavers in four California fisheries. CalCOFI Reports, 56: 1–10.

Haynie, A. C., and Layton, D. F. 2010. An expected profit model for monetizing fishing location choices. Journal of Environmental Economics and Management, 59: 165–176.

Hicks, R. L., and Schnier, K. E. 2008. Eco-labeling and dolphin avoidance: a dynamic model of tuna fishing in the Eastern Tropical Pacific. Journal of Environmental Economics and Management, 56: 103–116.

Hirschman, A. O. 1964. The paternity of an index. The American Economic Review, 54: 761–762.

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

Kahui, V., and Alexander, W. R. J. 2008. A bioeconomic analysis of marine reserves for Paua (Abalone) Management at Stewart Island, New Zealand. Environmental and Resource Economics, 40: 339–367.

Kasperski, S., and 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.

King, J. R., Agostini, V. N., Harvey, C. J., McFarlane, G. A., Foreman, M. G., Overland, J. E., Di Lorenzo, E., *et al.* 2011. Climate forcing and the California Current ecosystem. ICES Journal of Marine Science: Journal du Conseil, 68: 1199–1216.

Leising, A. W., Schroeder, I. D., Bograd, S. J., Abell, J., Durazo, R., Gaxiola-Castro, G., Bjorkstedt, E. P., *et al.* 2015. State of the California Current 2014-15: Impacts of the Warm-Water "Blob". CalCOFI Reports, 56: 31–68.

Lindley, S. T., Grimes, C. B., Mohr, M. S., Peterson, W., Stein, J., Anderson, J. T., Botsford, L. W., *et al.* 2009. What caused the Sacramento River fall Chinook stock collapse? NOAA Tech Memo NMFS-SWFSC, NOAA-TM-NMFS-SWFSC-447.

López-de-Lacalle, J. 2015. tsoutliers: Detection of Outliers in Time Series. R package version 0.6. Available at https://cran.r-project.org/web/packages/tsoutliers/tsoutliers.pdf (last accessed 27 April 2017).

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

McKibben, S. M., Peterson, W., Wood, A. M., Trainer, V. L., Hunter, M., and White, A. E. 2017. Climatic regulation of the neurotoxin domoic acid. Proceedings of the National Academy of Sciences of the United States of America, 114: 239–244.

Nakagawa, S., and Schielzeth, H. 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods in Ecology and Evolution, 4: 133–142.

PacFin (Pacific Fisheries Information Network). 2016. retrieval dated 3/16/2016, Pacific States Marine Fisheries Commission (PSFMC), Portland, Oregon (www.psmfc.org).

Peterson, W., Bond, N., and Robert, M. 2016. The Blob is gone but has morphed into a strongly positive PDO/SST pattern. PICES Press, 24: 46.

Peterson, W., Robert, M., and Bond, N. 2015a. The warm blob continues to dominate the ecosystem of the northern California current. PICES Press, 23: 44.

Peterson, W., Robert, M., and Bond, N. 2015b. The warm blob-Conditions in the northeastern Pacific Ocean. PICES Press, 23: 36.

PMFC (Pacific Fishery Management Council). 2016. Review of 2015 Ocean Salmon Fisheries: Stock Assessment and Fishery Evaluation Document for the Pacific Coast Salmon Fishery Management Plan. (Document prepared for the Council and its advisory entities), Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.

R Development Core Team. 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statstical Computing, Vienna, Austria.

Rousseeuw, P., Croux C., Todorov, V., Ruckstuhl, A., Salibian-Barrera, M., Verbeke, T., Koller, M. *et al.* 2016. robustbase: Basic Robust Statistics. R package version 0.92-6.

Schielzeth, H. 2010. Simple means to improve the interpretability of regression coefficients. Methods in Ecology and Evolution, 1: 103–113.

Schroeder, I. D., Black, B. A., Sydeman, W. J., Bograd, S. J., Hazen, E. L., Santora, J. A., and Wells, B. K. 2013. The North Pacific High and wintertime pre-conditioning of California current productivity. Geophysical Research Letters, 40: 541–546.

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

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

Smith, M. D., and Wilen, J. E. 2003. Economic impacts of marine reserves: the importance of spatial behavior. Journal of Environmental Economics and Management, 46: 183–206.

Sydeman, W. J., Thompson, S. A., García-Reyes, M., Kahru, M., Peterson, W. T., and Largier, J. L. 2014. Multivariate ocean-climate indicators (MOCI) for the central California Current: Environmental change, 1990–2010. Progress in Oceanography, 120: 352–369.

Todorov, V., and Filzmoser, P. 2009. An Object-Oriented Framework for Robust Multivariate Analysis. Journal of Statistical Software, 32: 1–47.

Ward, J. M., and Sutinen, J. G. 1994. Vessel entry-exit behavior in the Gulf of Mexico shrimp fishery. American Journal of Agricultural Economics, 76: 916–923.

Zeileis, A., Leisch, F., Hornik, K., and Kleiber, C. 2002. strucchange: an R package for testing for structural change in linear regression models. Journal of Statistical Software, 7: 1–38.

Zhang, J., and Smith, M. D. 2011. Heterogeneous response to marine reserve formation: a sorting model approach. Environmental and Resource Economics 49: 311–325.

Zwolinski, J. P., and Demer, D. A. 2012. A cold oceanographic regime with high exploitation rates in the Northeast Pacific forecasts a collapse of the sardine stock. Proceedings of the National Academy of Sciences of the United States of America, 109: 4175–4180.

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