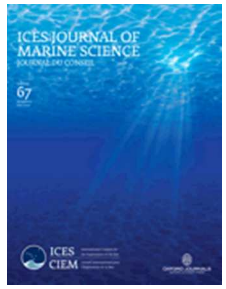

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Quantifying drivers of gear choice in the US West Coast sablefish fishery to improve future fisheries management

Kelli F. Johnson[1*], Sarah Klain[2], Ana K. Spalding[3,4], and Nadine Heck[5]

[1]School of Aquatic and Fishery Sciences, University of Washington, Box 355020 Seattle, WA 98195-5020, USA

[2]Institute for Resources Environment and Sustainability, University of British Columbia, Vancouver BC V6T 1Z4, Canada

[3]Smithsonian Tropical Research Institute, Apartado Postal 0843-03092, Panamá, República de Panamá

[4]School of Public Policy, Oregon State University, 318 Fairbanks Hall, Corvallis, OR 97331, USA

[5]Institute of Marine Sciences, University of California, 1156 High St., Santa Cruz, CA 95064, USA

[*]Corresponding author: tel (+1 206 543 4270); fax (+1 616 8689); email (kfjohns@uw.edu)

Abstract

Reducing catch of non-target individuals and species (i.e., bycatch) remains a global fisheries management issue and is consistently listed as one of several impediments towards achieving sustainable fisheries. A variety of management constraints may be implemented to achieve reductions in bycatch, but costs, both economic and societal, potentially vary between options and are difficult to predict. To date, much research has focused on the technical and economic aspects of bycatch reduction and incentives leading to the use of bycatch reduction technologies are typically assumed rather than assessed. Retrospective data from the US West Coast sablefish fishery were used to investigate changes in fishermen behaviour under two management alternatives (bi-monthly total allowable catches and individual transferable quotas). Changes in fishermen behaviour are relevant to management because they may influence catch and bycatch. For instance, whether fishermen choose to land sablefish by trawling or setting pots can lead to significant differences in realized bycatch because for most species bycatch rates are gear specific. Results from linear mixed effects models indicate fishermen have an increased

propensity to catch sablefish using fixed gear, potentially in an economically inefficient manner, when total allowable catch limits for bycatch species are constraining. Furthermore, ecological processes can be drivers of gear choice, when fishermen have the ability to switch gears. Research highlights the need for collecting data on local governance structures, such as membership in and/or rules of risk pools, such that socio-economic drivers of fishermen behaviour can be better quantified in increasingly transdisciplinary analyses.

Keywords: bycatch, catch share, governance, individual transferable quota (ITQ), risk pool, transdisciplinary

1 Introduction

Regulatory mechanisms to promote sustainable fisheries often involve restrictions regarding permissible activities of fishermen and typically include regulating when, where, how, and how much fishermen can catch. Outcomes of these regulatory mechanisms, often expressed in terms of number of fish caught, can depend, sometimes non-linearly, on multiple factors. Furthermore, combinations of mechanisms can lead to outcomes unachievable by any single mechanism (Lewison *et al.*, 2011; Deacon, 2012; Ono *et al*., 2013). Consequently, appropriate solutions to fisheries management problems are contextual, dependent on human behaviour, and embedded in complex social-ecological systems (Hilborn, 2007; Kaplan *et al*., 2010).

The unselective nature of many types of fishing gear is recognized as a global fisheries management problem. For example, the Food and Agricultural Organization in the Code of Conduct for Responsible Fisheries Mandates (FAO, 1995) and the United States (US) in the Magnuson-Stevens Fishery Conservation and Management Act (MSA; 16 U.S.C. § 1802(2)) mandate for minimizing the catch of non-target individuals and species, hereafter referred to as bycatch. Literature suggests that regulatory mechanisms to reduce bycatch are potentially straightforward and achievable by means of gear modifications, avoidance incentives, spatial or temporal closures, or some combination thereof (Hall and Mainprize, 2005). Unfortunately, solutions that are effective over the long-term can be situational and require understanding more than patterns in gear selectivity, such as local governance structures, species life-history characteristics, and fishermen education level (Lewison *et al*., 2011; Senko *et al*., 2014, Teh *et al.*, 2015). To date, much of the literature on bycatch reduction remains sectoral in nature, and excludes human behaviour. Therefore, transdisciplinary methods such as those proposed in this paper and in Teh *et al*. (2015) provide an integrated approach for investigating the political, economic, and ecological drivers of bycatch. Specifically, this paper analysed changes in the behaviour of US West Coast groundfish fishermen given changes in management and their bycatch implications.

Effective bycatch management must fit in with the overall goals of fisheries management (e.g., those defined in the MSA), where most management frameworks operate with the main goals of ensuring sustainable fisheries and viable fishermen livelihoods. No strategy to reduce bycatch is perfect and each offers their own tradeoffs. For instance, per-unit taxes on bycatch, payable by individual fishermen, are known for promoting fishermen to engage in environmentally sustainable behaviour, but fail to place a hard cap bycatch limits and may overly constrain the fishery when bycatch rates are highly variable (Herrera, 2005; Singh and Weninger, 2009). Conversely, total allowable catch (TAC) policies guarantee observation of bycatch limits, but promote inefficiency when quota for profitable species remains unfilled (Androkovich and Stollery, 1994; Holland, 2010; Patrick and Benaka, 2013). Individual transferable quotas (ITQs), where fishermen are allocated shares of the TAC, are theorized to reduce bycatch by encouraging fishermen to change their behaviour in a way that reduces catches of species for which quota is scarce (Casey, 1995; Hall *et al*., 2000; Holland and Jannot, 2012). ITQs therefore eliminate the need for mandated time and area closures, which theoretically become increasingly self-regulated as quota becomes scarcer.

Within ITQ fisheries, quota markets offer one means to rectify imbalances between catches and quota, while maintaining a low risk of overexploitation (Sanchirico *et al*., 2006). Theoretically, market prices in efficient markets (i.e., a large number of buyers and sellers, low transaction costs, and readily available price information) should reflect differences between expected price and cost on a per fish basis (Fama, 1970; Stavins, 1995; Swinkels, 1999). Unfortunately, quota markets tend to be inefficient, with few sellers and exhibit high transaction costs (Newell *et al*., 2005; Holland, 2013; Holland *et al*., 2015). Risk pools, where fishermen pool their quota of non-target species, offer a potential means to mitigate financial risk and reduce transaction costs of quota markets while maintaining a high probability that catches will not exceed TACs. Risk pool members must agree to stop fishing (for all species) when the aggregate bycatch of the pool members exceeds the pool's quota.

Gear switching offers another tool for reducing bycatch (FAO, 2010). In general, fixed gears such as longlines and pots are more selective than active gears like trawls but the potential benefits of switching must be weighed against possible costs (Table 1). Costs could include such things as differences in habitat impacts, economic loss from purchasing new gear, etc. If switching from trawls, which are known for exhibiting imperfect selection and thus high bycatch (Andrew and Pepperell, 1992; Kennelly, 1995; Hall *et al*., 2000), to fixed gear, managers must also account for potential decreases in catches of other target species because trawl gear is often used in multispecies fisheries. Even if management does not allow for fishermen to switch gears, trawl fishermen usually have at least a limited ability to control the ratio of species caught within their net (Beverton and Holt, 1957; Campbell and Nicholl, 1994; Quirijns *et al*., 2008). Unfortunately, most management systems fail to provide incentives or the flexibility to fishermen to alter their behaviour (Branch *et al*., 2006; Abbott and Wilen, 2009). Furthermore, it is often difficult for managers to determine *a priori* how fishermen will behave if given the opportunity to alter their behaviour.

Understanding when fishermen switch gears, join a risk pool, or move to a new fishing location (i.e., fishermen behaviour) within the constraints of management and fish life-history characteristics has the potential to increase management efficiency and promote sustainability. Factors related to fish ecology, economics, and management were used to understand gear choice while landing sablefish (*Anoplopoma fimbria*) in the US West Coast groundfish fishery. Yearly port specific sablefish trawl landings relative to landings from all gear types were investigated using generalized linear mixed effects models. Results provide insights relevant to the design and implementation of ITQ policies, particularly those dealing with bycatch issues. Additionally, challenges regarding assimilating data across multiple disciplines are discussed.

2 Methods

2.1 Overview

Fishery-dependent and -independent data were used to build a mixed effects model to assess the relative contribution of ecological, economic, and management covariates on the proportion of sablefish landings caught by trawl gear relative to all gear types. Integrating data collected from multiple disciplines in a single model facilitates analysing fishermen behaviour from a socio-economic perspective, which is necessary step forward for all analyses wishing to enable sustainable fisheries.

2.2 Case study background

Today, sablefish is one of the most valuable fisheries in the US West Coast groundfish fishery, a federally managed multispecies fishery encompassing over 90 species but primarily targeting demersal species such as sablefish, Dover sole (*Microstomus pacificus*), shortspine thornyhead (*Sebastolobus alascanus*), Petrale sole (*Eopsetta jordani*), and Pacific whiting (Pacific hake, *Merluccius productus*). Reconstructed sablefish landings go back to the early 1900s, with the California Department of Fish and Wildlife documenting some of the first records in 1908 (Figure 1). Prior to 1960, landings were primarily caught using hook and line, with later increases in the 1970s attributed to the development of a foreign vessel pot fishery (McDevitt, 1986). With the implementation of the MSA and the creation of the Pacific Fisheries Management Council (PFMC) Groundfish Fishery Management Plan, management authority switched from individual coastal states to the federal government, with the first federal regulation being coast-wide trip limits implemented in October of 1982 (Johnson *et al*., 2015).

Increasing effort and decreasing stock size led to the implementation of seasonal management, gear specific allocations, and limited entry (LE) permits. By 1994, the fishery was apportioned 90.6% to the LE permit program, further split 58 – 42% between the LE trawl and the LE fixed gear sectors, and 9.4% to an open access fishery, where the open access fishery was designed for vessels that did not qualify for the LE program based on meeting landing requirements between July 11, 1984 and August 1, 1988. One permit was issued per vessel, though each permit could hold multiple gear endorsements. Additionally, management was spatially divided with higher TACs north of 36° N compared to south of 36° N.

Increasing concerns for fishermen safety associated with decreasing season lengths, just five days in 1996, led to the 2002 implementation of a three-tier quota system for the LE fixed gear fishery.

Allocations of TAC, tied to a permit, were based on historical landings and vessels could stack up to three permits. Seasons were still necessary such that the tiers did not represent an ITQ system, which were not allowed under the MSA moratorium on new ITQ programs. An exception to the moratorium was made for the sablefish fixed gear LE permit fishery on August 2, 2001 (PFMC, 2001), and despite the 2002 expiration of the moratorium, the trawl fishery was managed primarily through vessel bimonthly cumulative landing limits and spatial closures until 2011.

In 2011, an ITQ system was introduced for all participants of the US West Coast LE groundfish trawl fishery, with allocations of targeted species based on historical landings. In addition to target species TAC limits, management includes bycatch limits for Pacific halibut (*Hippoglossus stenolepis*), an internationally managed species, and five overfished species (Table 1): (a) bocaccio (*S. paucispinis*; Field, 2013); (b) cowcod (*S. levis*; Dick and MacCall, 2014); (c) darkblotched rockfish (*S. crameri*; Gertseva and Thorson, 2013); (d) Pacific ocean perch (POP, *S. alutus*; Hamel and Ono, 2011); and (e) yelloweye rockfish (*S. ruberrimus*; Taylor and Wetzel, 2011). Allocations for most bycatch species are based on bycatch rates applied to target species allocations (PFMC and NMFS, 2010). Furthermore, in 2011, bycatch TAC became binding, whereas previously fishermen could continue fishing as long as all species for which they had reached their quota were discarded. Thus, incentives to reduce bycatch were potentially made stronger and individuals' concerns about risk regarding reaching bycatch TAC limits led to the formation of multiple formal and informal risk pools. Risk pools are a very distinct form of fishery governance, as they involve contractually binding private agreements based on a set of rules by which all members must abide, and they can enable non-governmental organizations to be major players of fisheries management, management which is usually controlled by governmental institutions (Little *et al.*, 2015).

As of 2013, 164 vessels held sablefish permits and forty of those utilized the permit stacking program (PFMC and NMFS, 2014). With six permits having endorsements for multiple gear types: four longline and pot, one pot and trawl, and one longline and trawl. Prior to 2014 vessels could only sell quota pounds (i.e., annual amount a fisherman is allowed to catch) and not quota shares (i.e., allocation of TAC).

2.3 Fishery-dependent data

Landings and ex-vessel revenue data from the US West Coast groundfish fishery are archived in the Pacific Fisheries Information Network (PacFIN) regional database, a compilation of sales receipts (i.e., fish-tickets) collected during the delivery of fish to processing plants in Washington, Oregon, and California (Pacific States Marine Fisheries Commission, Portland, OR, www.psmfc.org/pacfin). The database contains information on landings by gear and market category, where sablefish represent a market category. Data on vessel characteristics are collected by the Economic Data Collection (EDC) program, a mandatory component of the US West Coast groundfish trawl catch share program (West Coast Fisheries Economics Program, NOAA Fisheries, Seattle, WA, www.nwfsc.noaa.gov/research/divisions/fram/economic). Since 2009, all catch share participants are required to provide information on operating costs, revenue, and vessel characteristics including: length, horsepower, market value, fuel capacity, days at sea, fishing speed, variable and fixed costs, and net revenue.

PacFIN and EDC data were provided as port specific measures. Specifically, landings and ex-vessel revenue were summed by the port group at which they were landed and EDC data was summed or averaged by port group for which the each vessel had the highest ex-vessel revenue for that year. Where there were not enough observations to ensure confidentiality, such that no value represented fewer than 3 entities, and no one entity represented 90% of any individual statistic, data was not provided (16 U.S.C. § 1881a).

2.4 Fishery-independent data

The Northwest Fisheries Science Center (NWFSC) Shelf-Slope survey collects annual data on hundreds of fish species along the US West Coast (Bradburn *et al*. 2011). Contracted commercial fishing

192 vessels conduct standardized bottom trawl surveys at depths of 55 to 1280 m from Cape Flattery,
193 Washington (48° 10'N) to the US-Mexico border (32° 30'N). Typically the survey contracts four vessels
194 per year, although 2012 involved 2 contracts to a single vessel. The entire survey area is usually covered
195 twice per year using a stratified random sampling design (based on three depth categories), with sampling
196 extending from late May to late July for the first pass and from mid-August to late October for the second
197 pass. Data are used as the primary source of abundance information for most PFMC groundfish stock
198 assessments. Specifically, relative indexes of abundance are generated using the spatially resolved (trawl
199 mid-point) species-specific catches (West Coast Groundfish Bottom Trawl Survey, NOAA Fisheries,
200 Seattle, WA) and delta generalized linear mixed-effects models (delta-GLMMs), which can account for
201 vessel 'catchability', spatiotemporal variability, and uncertainty arising from small sample sizes or
202 extreme catch events (Thorson and Ward, 2013).

203 Relative indexes of abundance by strata for sablefish and four overfished species were estimated
204 using delta-GLMMs implemented with an open source software package (Thorson and Ward, 2013) in
205 the R statistical software environment (R Core Team, 2015). Although cowcod is currently declared
206 overfished, it was not included because spatial management (Rockfish Conservation Areas) has been
207 successful in decreasing instances of bycatch and as a species they represent the smallest (sometimes
208 zero) percent of bycatch within the sablefish fishery (NMFS, 2004). Strata were defined by latitudinal
209 breaks (46°30'N, 45°N, 44°N, 43°N, 41°30'N, 40°30'N, 39°N, and 37°N; Figure 2) which correspond
210 with fishing out of major ports and prominent biogeographic features at Cape Blanco, OR (42° 50`N) and
211 Cape Mendocino, CA (40° 26`N): (1) Washington, (2) Astoria and Tillamook, (3) Newport, (4) Coos
212 Bay, (5) Brookings and Crescent City, (6) Eureka, (7) Fort Bragg, (8) San Francisco and Bodega Bay, and
213 (9) Monterey and Morro Bay. Furthermore, strata correspond to port groups from the PacFIN and EDC
214 data.

215 Delta-GLMMs facilitate the inclusion of vessel:year interactions as random effects, which is
216 necessary because vessels were not consistent across years (Helser *et al*., 2004). Gamma error structures
217 were used for model components representing positive catches and a Bernoulli error structure was

assumed for all presence/absence components. Stratum, vessel, and year effects were investigated, leading to five model structures for each species: (a) strata and year as fixed effects and the interaction of year and vessel as random effects; (b) strata and year and the interaction between strata and vessel as fixed effects; (c) strata and year as fixed effects and the interactions between year and vessel and strata and vessel as random effects; (d) strata and year as fixed effects; and (e) strata and year as fixed effects with correlated interactions between year and vessel and strata and vessel. Additionally, all models included survey pass as a covariate to account for incomplete sampling during the second pass of the 2013 survey where stations south of 37°N were not sampled. Model goodness of fit was evaluated using Bayesian posterior predictive checks and model selection was performed using deviance information criterion (Spiegelhalter *et al*., 2002).

2.5 Statistical analysis

Generalized linear mixed effect models (Pinheiro and Bates, 2000) were used to provide inference regarding the proportion of sablefish landings caught by trawl gear as compared to other gear types in the US West Coast sablefish fishery. GLMMs are extensions of linear models with an added random component, $Z\mu$, which provides the flexibility needed to model the statistical means of the hierarchical data, which lack independence, and their variance and covariance. Using matrix notation,

$$y = X\beta + Z\mu + \epsilon, \qquad \text{Equation 1}$$

y is the vector representing the dependent variable, $X\beta$ represents the fixed portion of the model such that X denotes the design matrix ($n\ x\ p$) of fixed effects and β denotes a vector of length p holding the fixed intercept and slopes, μ is the vector of length q holding the random intercepts and/or slopes, Z is the random effects design matrix ($n\ x\ q$), and ε is normally distributed with a mean of zero and a variance of σ^2. Here, $Z\mu$ allowed for variations among port groups. Temporal random effects could also be included to account for correlation between years, though this was not investigated here.

The dependent variable, proportion of total landings caught by trawl gear, was bounded between zero and one, thus a Beta distribution was deemed appropriate (Crowder, 1978, Smithson and Verkuilen, 2006). The Beta distribution is a continuous distribution with finite support on [0, 1], and is governed by two shape parameters, a and b (Beta(1, 1) is equivalent to a uniform distribution):

$$f(x;a,b) = \frac{1}{B(a,b)} x^{a-1}(1-x)^{b-1} \qquad \text{Equation 2}$$

where $B(a,b)$ is a normalization constant defined via Euler's Γ function, $\Gamma(a+b)/\big(\Gamma(a)\Gamma(b)\big)$. The Beta distribution cannot model non-uniform densities with probability mass at zero or one. Unfortunately, the data included a non-negligible number of ones, thus a one-inflated Beta distribution, a mixed continuous-discrete distribution with an additional parameter, ν, that allows ones, was used (Ferrari and Cribari-Neto, 2004). Thus, $(\nu - 1) * Beta(a,b)$, represents the case where $y = (0,1)$.

Fixed effect covariates pertained to port specific mean characteristics of trawl vessels ((a) fuel consumption, (b) speed, (c) crew size, (d) fixed costs, (e) variable costs), indexes of abundance for four overfished species ((a) bocaccio, (b) darkblotched rockfish, (c) Pacific ocean perch, and (d) yelloweye rockfish), and an indicator variable for before or after the 2011 implementation of catch shares. Continuous fixed effect covariates were z transformed, $((x - mean(x))/sd(x))$, so that the mean of each variable was zero and the range was roughly between negative three and three. Only linear relationships without interactions were investigated because of the short time series available (i.e., EDC data collection began in 2009). The *a priori* hypothesized model set includes five models:

1. proportion ~ 1 (intercept);
2. proportion ~ 1 + management (manage);
3. proportion ~ 1 + bocaccio + yelloweye rockfish + darkblotched rockfish + Pacific ocean perch (ecology);
4. proportion ~ 1 + speed + crew size + fixed costs + variable costs + fuel use (economics); and
5. proportion ~ 1 + bocaccio + yelloweye rockfish + darkblotched rockfish + Pacific ocean perch + speed + crew size + fixed costs + variable costs + fuel use (all).

Analyses were performed using the Generalized Additive Models for Location, Scale, and Shape (*gamlss*) package (Rigby and Stasinopoulos, 2005) in the R statistical environment (R Core Team, 2015). GAMLSS allows the location parameter (*mu*) and scale and shape parameters related to dispersion, skewness, and kurtosis of the distribution to be modelled as functions of covariates and/or random effects.

Given that all models were fit to the same data but contained a different number of parameters, model goodness of fit was determined using Akaike's Information Criterion (AIC; Burnham and Anderson, 2002). The model with the lowest AIC provides the most parsimonious representation of the data and models with differences of less than two are seen as having similar fits. AICc, which provides a greater penalty for extra parameters, was used to prevent overfitting given the small sample size:

$$AICc_k = 2P_k - 2\ln(L_k) + \frac{2P_k(P_k+1)}{n-P_k-1} \qquad \text{Equation 3}$$

where n denotes the sample size, P_k is the number of parameters in model k, and L_k is the maximized likelihood of model k. Additionally, all models were checked for independence of the residuals by means of visual inspection of residual plots (e.g., residuals vs response and qq-plots).

3 Results

3.1 Index of abundance

Sablefish were found throughout the range surveyed by the NWFSC Shelf-slope survey, while each overfished species was less ubiquitously distributed (Figure 3). The distribution of cowcod was the most protracted being found mainly off the coast of California. Of the overfished species, the presence of darkblotched rockfish was the most uniform throughout the study area, though they were rarely found in the southern California region.

In areas off the coast of southern Oregon and northern California, relative indices of abundance appeared to be stable for most species (Figure 4). Notably, bocaccio and Pacific ocean perch appear to be increasing in southern California and Washington, respectively. The relative index of abundance for

292 sablefish appears to be relatively stable in all areas. The larger relative index of abundance for sablefish
293 for the southern California region relative to the other eight regions is to be expected, given that southern
294 California represents a much larger area.
295
296 3.2 Generalized linear mixed effects model
297 To protect fishermen confidentiality, sample sizes for some areas were smaller than others, limiting the
298 statistical power of the model. Limitations were particularly noticeable regarding the inability to test for
299 interactions between biological and economic covariates and the management dummy variable, where all
300 years prior to 2011 were coded as "before" and years equal to or greater than 2011 were denoted as
301 "after". Port groups "Astoria and Tillamook" and "Brookings and Crescent City" were the only two port
302 groups with information available for the entire period (2009 to 2013; Table 2).
303 Preliminary investigations revealed that the second parameter of the beta distribution, b, and the
304 parameter governing the presence or absence of ones, ν, were best modelled as random effects, where
305 random effects were included to accommodate repeated measures across years for each port group and all
306 investigated models included the same random effect structure. The estimated effective degrees of
307 freedom for ν were the same across all investigated models (Table 3). Conversely, as the model structure
308 included more fixed effects, the estimated effective degrees of freedom for b increased (Table 3).
309 The most parsimonious model was one that included management and biological covariates
310 (Table 3). For this model, the residuals had a mean -0.60, a variance of 0.58, a coefficient of skewness of
311 -0.48, a coefficient of kurtosis of 3.29, and a Filliben correlation coefficient of 0.98. Modelled
312 coefficients indicate that as the relative abundance of yelloweye rockfish, darkblotched rockfish, and
313 bocaccio increased, the conditional expected proportion of sablefish landings caught by trawl gear also
314 increased while the opposite is true for relative index of abundance for Pacific ocean perch (Table 4).
315 Additionally, the conditional expected proportion of sablefish landings caught by trawl gear is estimated
316 to decrease in years greater than or equal to 2011. Coefficients for before management (Intercept),

bocaccio, and ν were not significant at the 0.05 level but were kept in the model because reduced models were not included in the *a priori* hypothesized model set.

Comparisons of model coefficients across models must be done carefully, as each coefficient must be interpreted on the logit scale with respect to the estimated intercept. Estimated coefficients for variable and fixed costs (increase and decrease in odds ratio, respectively) were similar between the economics and all models (Table 5). Conversely, estimated coefficients for fuel use and all biological covariates varied in direction between their respective models and the model that included all coefficients.

3.3 Potential changes in bycatch

For all species currently listed as overfished, Jenkins and Garrison (2012) report a higher bycatch rate (per 100 kg of landed sablefish) when fishing with trawls than pots or longlines, except for yelloweye rockfish where bycatch using longlines is higher than for trawl (Table 1). Results indicate that the change in management led to a decrease in the proportion of sablefish landings caught by trawl gear. Specifically, the most parsimonious model predicts a 30% decrease in the odds ratio after 2010 (Table 4). Additionally, the model predicts a decrease in the odds ratio with increasing relative abundance of Pacific ocean perch, potentially meaning that in areas of increased relative abundance of Pacific ocean perch fishermen are increasing their use of fixed gear and potentially decreasing their realized bycatch of Pacific ocean perch. The opposite effect was estimated for yelloweye rockfish, which could potentially mean reduced bycatch of yelloweye rockfish if fishermen are switching from longline to trawl gear in these areas.

4 Discussion

Given that all three gear types utilized in the US West Coast sablefish fishery imperfectly select fish in their own unique way (i.e., each gear selects only a portion of available ages or sizes while also selecting other species), leading to gear specific bycatch rates, it is important to understand what drives fishermen to choose one gear type over another. It was found that ecological and management factors had an increased ability to predict the proportion of sablefish landed using trawl gear compared to economic factors, suggesting that within the constraints of management, decisions regarding gear choice rely on more than just dollars and cents. Results highlight the benefits of methods that integrate knowledge from multiple disciplines into a single study, building on traditional disciplinary research which was instrumental in highlighting the need to account for socio-cultural and –economic factors inherent in fishery management issues (Komoroske and Lewison, 2015).

A number of factors limit fishermen's ability to switch gears: resistance to change, lack of economic incentives, incompatibility between vessels and gear, operator experience, and safety of the vessel and crew (Jenkins and Garrison, 2013). Thus, when given a choice (i.e., allowed to within the management framework) not all fishermen will choose to switch gears even if it makes sense economically. Economic covariates were estimated with low standard errors, except for average vessel speed, but the data was fit equally as well when only modelling the mean (intercept only model). Clearly, one should be able to do better than the mean model, which overestimates the true proportion of landings caught using trawl gear (Johnson *et al.*, 2015). Results should be interpreted in light of several considerations, and not that economics fail to play a role in gear choice. Only a subset of all possible models were included in the *a priori* set, thus future work could consider other economic covariates or explore additional model structures, such as those that contain a subset of economic and ecological covariates or allow for temporal lags. Assigning vessel characteristics to port group based on the port of highest ex-vessel revenue may not coincide with port of landing and vessel specific data should be investigated in future models. Finally, it is possible that we have yet to see the economics of gear switching play out given that selling ones quota shares was only recently allowed.

A gear switching feasibility study, conducted prior to the implementation of catch shares, found that incentives were likely to be needed to encourage fishermen to engage in long-term gear conversion even though during interviews many noted that switching from trawls to fixed gear would result in lower bycatch (Jenkins and Garrison, 2012). Of all the investigated ecological covariates, only increases in the relative abundance of Pacific ocean perch, the species with the largest disparity between gear-specific bycatch rates (Jenkins and Garrison, 2012; Holland and Jannot, 2013), led to a decline in the estimated proportion of landings caught using trawl gear. A result which corroborates Jenkins and Garrison's (2012) finding that fishermen may require incentives to switch from trawl gear to gear with a lower risk of bycatch because of potential decreased landings of other target species.

Methods presented here may be useful in evaluating how much of a disparity between gear-specific bycatch rates is needed for fishermen to switch gears. Model coefficients for yelloweye and darkblotched rockfish both predicted increases in the proportion of sablefish caught by trawl gear with increases in their relative abundance, suggesting disparity between bycatch rates were not large enough to encourage gear switching. Future methods should attempt to account for seasonal changes in bycatch rates, as fishermen may alter their location when the risk of bycatch is higher for species like darkblotched rockfish which exhibit quarterly differences in both survey and fishery bycatch rates (Jannot and Holland, 2013). Trawlers showed limited desire to switch from trawling to longlines and thus it makes intuitive sense that gear switching would not be encouraged under either management framework with increasing relative abundance of yelloweye rockfish because trawl and pot bycatch rates of yelloweye are essentially zero (Jenkins and Garrison, 2012).

For species like bocaccio, where bycatch rates are constant among gear types and estimated covariates are not statistically significant, it is likely that spatial overlap does not occur between the target and bycatch species within the fished areas. Determining if the lack of overlap is driven by management or ecology would be possible by analysing co-occurrence of bycatch and target species using fishery-independent and -dependent data that is more spatially resolved (Jannot and Holland, 2013). We hypothesize that results would be similar for cowcod, given that spatial closures have been successful in decreasing their bycatch rates. Although one should note that those spatial closures came at some cost to fishermen, i.e., increased distances from ports to offshore areas where sablefish are typically targeted and increased fishery exit rates in some areas (Manson *et al.*, 2012). As the time series lengthens it may be feasible to test interactions between shifts in policy and ecological covariates, providing further information on potential reasons for changes in fishermen behaviour or lack thereof.

Quota share allocations for each overfished species were assigned based on bycatch rates applied to allocated quota shares of targeted species. Thus a fisherman who historically targeted sablefish using trawl gear would have received a very small quota share of yelloweye. With the moratorium on selling quota shares and binding TACs for overfished species, this fisherman could potentially be limited in his/her ability to switch to using longlines, which has a higher bycatch rate for yelloweye than trawl gear, unless he or she could find additional quota pounds for purchase. It appears as though fishermen are risk averse now that TACs are binding, as correlation between fishermens' allocated quota pounds of bycatch species and catch are low (Holland 2012). Risk pools may mitigate the risk of fishermen not being able to find additional quota pounds, and their existence and/or membership rules may be a significant driver of gear choice (Fehr and Leibbrandt, 2010). Unfortunately, within the US West Coast groundfish fishery, risk pools are not required to publicly disclose information on rules, membership, or outcomes and thus it was not feasible to include the number of risk pool participants per port group in this analysis.

Currently, The Nature Conservancy (TNC) owns quota shares within the US West Coast groundfish fishery and leases quota pounds to members of the California risk pool, in return for having a say in how fishing occurs. In turn TNC has helped implement a geographic information system combining science and technology with fishermen's knowledge, historical data, and habitat information to identify zones that contain overfished species in near real-time as well as implemented voluntary spatial closures of high risk areas when combined quota for overfished species becomes limited (Bjorkland *et al.*, 2015). According to TNC, since initiating the California Risk Pool, members have experienced reduced bycatch of overfished species, increased harvest of target species, and improved the tracking and sharing of fishing information (TNC, 2014).

While risk pools might thus reduce bycatch and discards for its members, they pose multiple challenges for fisheries including: the assignment of each individual's risk of overfishing into a single pool and implementing spatial-temporal closures that are focused on reducing bycatch and may not be optimized for all target species in a multispecies fishery or for fishermen equity among sectors (Bjorkland *et al.*, 2015). Additionally, risk pools can potentially result in unequal social and economic impacts through inclusion/exclusion policies potentially creating an imbalance in the fishery in terms of access to social networks, information, and income potential between members and non-members. So far, it remains unknown if risk pools are socially just or create a kind of elite group (Deacon, 2012) and if their formation motivates the "race to fish" thereby undermining the ITQ system (Holland and Jannot, 2012). Unfortunately, we were not able to determine if participation in risk pools led to changes in fishermen behaviour and consequently bycatch of overfished species because of the lack of data.

ITQ systems are consistently promoted for their ability to increase resource stewardship by transferring ownership to individual fishermen. Results clearly indicate that fishermen decreased their use of trawl gear for landing sablefish after the implementation of catch shares in 2011, but it remains unknown if this was because of bycatch TAC constraints; economic incentives, such as higher prices per pound for sablefish landed using fixed gear; a desire to fish in areas where trawl gear is restricted; or some other factor. Economic data were available on vessels using fixed gear, which could have helped tease apart some of the hypotheses, but they were not included in the analysis because of limited sample sizes given confidentiality constraints. Nevertheless, the framework presented here offers those with access to the full data set to model changes at the vessel level which would perhaps provide increased insight on the drivers of gear switching beyond the fact the political environment allowed for it.

Future work could focus on validating the framework through port specific fishermen surveys, with questions specifically related to decision-making processes that could then be related to the findings of the model. Once decision-making strategies were identified, a subset of the surveyed fishermen could be interviewed to gain in-depth understanding of the various adaptive strategies they use to improve their economic gains (recognizing it is dependent on the existence of a sustainable fishery). Additionally, now that fishermen are allowed to switch gears, a more informed scenario analysis could be conducted. While this would likely add an unnecessary amount of information to an already complex, federally-mandated, fisheries management policy, it could contribute to an informal system of information sharing of best practices aimed at supporting and improving social and ecological fisheries sustainability. Furthermore, refining the methods defined in Jenkins and Garrison (2013) may increase their applicability to other fisheries.

Although bycatch reduction is best for sustainable fisheries, avoidance costs or reduced catches of target species suggest that reductions may not be internally consistent with facilitating profit maximization for individual fishermen (Abbott and Wilen, 2009; Singh and Weninger, 2009). Nevertheless, results demonstrate that fishermen can and are potentially willing to adapt their behaviour, within certain constraints. As outlined above, additional information is needed to determine the extent to which fishermen are willing to form associations or adopt alternative (federally allowed) governance structures. However, it is clear that incorporating information beyond traditional ecological data (e.g., crew size, relative indices of abundance) can help managers elicit the drivers of fishermen behavior. Additionally, in the absence of complete and perfect information, quantitative models could be supplemented with qualitative information obtained from fisheries and industry reports on adaptive responses to the bycatch problem. Binding bycatch TACs have raised the stakes and created additional risks to an already highly regulated fishery, leading to changes in fishermen behavior. Models, such as that presented here, contribute to a more complete and in-depth understanding of fisherman behavior and response to management, offering a framework to assess changes in fishermen behavior and their potential impact on bycatch within other fisheries.

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619 Table 1. Gear specific bycatch rates of seven rockfish species declared overfished in 2004 (some have
620 since been rebuilt) by trawl, longline, and pot gear in the US West Coast sablefish fishery. Reproduced
621 from Table 1 in Jenkins and Garrison (2013).

Overfished rockfish species (2004 status)	Bycatch ratio (kg of bycatch species caught per 100 kg of retained target catch)		
	Trawl	Longline	Pot
bocaccio	0-0.001	0	0
canary	0.009-0.010	0.070	0
cowcod	0	0	0
darkblotched	2.196-6.291	0.068	0.033
Pacific ocean perch	1.706-1.471	0.006	0.003
widow	0.013-0.140	0	0.001
yelloweye	0-0.004	0.037	0

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Table 2. Mean economic and vessel characteristics for trawl vessels in the US West Coast sablefish fishery. Values are summarized by port group, where some sample sizes (n) are less than the total number of years (2009 to 2013) to protect fishermen confidentiality. Port groups are listed in geographic order going from north to south. Vessels were assigned to port groups based on the port for which they had the highest ex-vessel revenue in that year.

Port group	n	Fixed costs	Variable costs	Crew	Fuel	Speed
Washington	4	235739.89	476719.73	2.35	366.90	3.13
Astoria and Tillamook	5	88462.96	328568.67	1.90	264.76	3.29
Newport	2	147822.86	286226.81	2.00	407.80	2.64
Coos Bay	2	63002.37	136119.23	2.14	251.68	2.15
Brookings and Crescent City	5	69382.86	254627.59	2.06	330.00	2.11
Eureka	2	78531.76	274664.05	2.02	222.92	2.13
Fort Bragg	2	120302.23	224171.79	2.13	299.09	3.28
San Francisco and Bodega Bay	3	46217.42	115772.62	1.90	376.27	2.37
Monterey and Morro Bay	4	118133.08	198066.75	1.83	219.19	3.89

630 Table 3. Estimated effective degrees of freedom (dof) for beta distribution shape and scale parameters (*a*
631 and *b*) and the probability of y=1 (ν) for the five investigated models (see methods section for a
632 description of each model) with model complexity increasing from right to left. Aikaike's Information
633 Criterion corrected for small sample sizes (AICc) is also reported for each model. The bold AICc value
634 indicates the model with the most parsimonious fit to the data.

metric	parameter	intercept	manage	biology	economics	all
	a	1.00	2.00	6.00	7.00	11.00
dof	*b*	5.82	5.80	6.00	6.14	9.39
	ν	7.20	7.20	7.20	7.20	7.20
AICc		63.35	71.84	**49.28**	64.30	3754.29

635

636

637 Table 4. Model coefficient results for the most parsimonious model (biology). Values are the natural log
638 of number of times higher/lower the ratio of the conditional expected proportion of sablefish trawl
639 landings is to the expected proportion of sablefish pot and longline landings, conditional on this
640 proportion not being one (1- *v*), with a one unit increase in the covariates. "Management after" is a
641 dummy variable taking on the value one for all years greater than or equal to 2011 (i.e., the year catch
642 shares were implemented). The second parameter of the beta distribution (*b*) is modelled using a log link,
643 rather than logit, and thus exp(*b*) should be interpreted as the mean of the *b* amongst port groups.
644 Parameter significance at the 0.05 level is indicated using bold face typeset.

Parameter	Estimate	Std. Error	Pr(> |t|)
Intercept	0.60321	0.35016	0.09837
management after	**-1.18947**	**0.35034**	**0.00249**
yelloweye rockfish	**0.46250**	**0.00691**	**0.00000**
darkblotched rockfish	**0.53522**	**0.00120**	**0.00000**
Pacific ocean perch	**-0.37337**	**0.00537**	**0.00000**
bocaccio	0.00693	0.07233	0.92448
***b* (log link)**	**10.58324**	**0.01134**	**0.00000**
ν	0.62266	0.47086	0.19974

645

646

Table 5. Model coefficient results for each of the five investigated models. Values are the natural log of number of times higher/lower the ratio of the conditional expected proportion of sablefish trawl landings is to the expected proportion of sablefish pot and longline landings, conditional on this proportion not being one (1- *v*), with a one unit increase in the covariates. “Management after” is a dummy variable taking on the value one for all years greater than or equal to 2011 (i.e., the year catch shares were implemented).

parameter	intercept	manage	ecology	economics	all
Intercept	-0.35192	0.03295	0.60321	1.75318	9.54726
management after		-0.38959	-1.18947	-2.73777	-8.82671
Crew				0.25036	1.15814
Fuel				0.57282	-1.74189
Variable costs				0.38539	2.38953
Fixed costs				-0.57747	-3.10953
Speed				0.39351	-3.60301
yelloweye rockfish			0.46250		-1.99698
Pacific ocean perch			-0.37337		0.72743
darkblotched rockfish			0.53522		-0.16582
bocaccio			0.00693		-0.29538

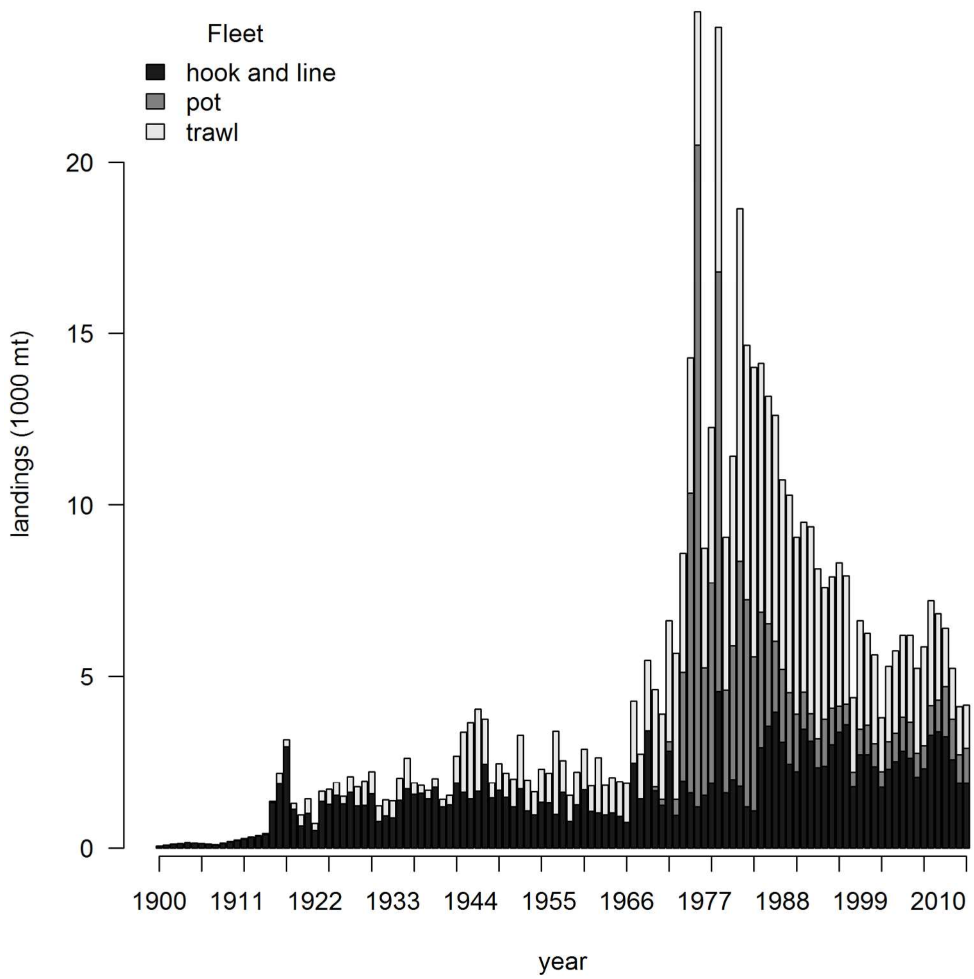
655 Figure 1. Reconstructed sablefish landings from 1900 to 2014. Landings include those from foreign
656 vessels, which are largely responsible for the peak landings in 1976 and 1979.
657

658 Figure 2. The geographical extent of the survey area with dashed latitudinal lines depicting strata used to
659 separate between port groups. Unique port groups from north to south include: (a) Washington; (b)
660 Astoria and Tillamook; (c) Newport; (d) Coos Bay; (e) Brookings and Crescent City; (f) Eureka; (g) Fort
661 Bragg; (h) San Francisco and Bodega Bay; and (i) Monterey and Morro Bay.
662
663

664 Figure 3. Positive tows (kg) from the Northwest Fisheries Science Center Shelf-slope survey from 2003
665 to 2014. Panels display data for a single species across all years, where the size of the transparent circle is
666 relative to the species specific weight in a given tow. From left to right, top to bottom, species are:
667 sablefish, Pacific ocean perch (POP), darkblotched rockfish, cowcod, boacaccio, and yelloweye rockfish.

668

669 Figure 4. Species specific relative indexes of abundances per port group estimated from delta-generalized
670 linear mixed effects models fit to data from the Northwest Fisheries Science Shelf-slope survey trawl.
671 Nine port groups (columns) along the US West Coast were included from Washington to the southern
672 California Mexico border: (A) Washington, (B) Astoria and Tillamook, (C) Newport, (D) Coos Bay, (E)
673 Brookings and Crescent City, (F) Eureka, (G) Fort Bragg, (H) San Francisco and Bodega Bay, and (I)
674 Monterey and Morro Bay. Results are presented for four overfished species and sablefish (rows). Indices
675 were generated using data from 2002 to 2014, but results are only shown for 2009 to 2013 because those
676 represent the years for which economic data was also available.



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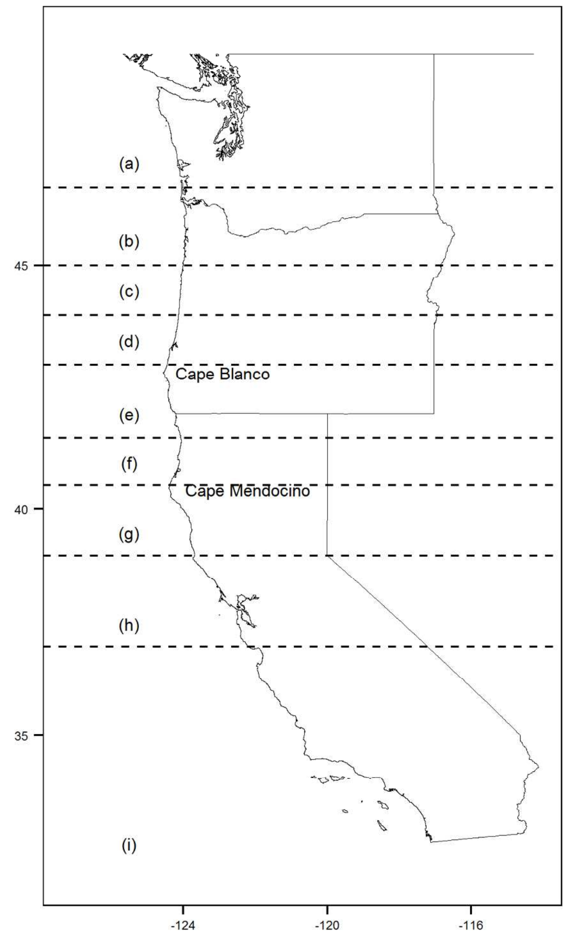

Figure 2. The geographical extent of the survey area with dashed latitudinal lines depicting strata used to separate between port groups. Unique port groups from north to south include: (a) Washington; (b) Astoria and Tillamook; (c) Newport; (d) Coos Bay; (e) Brookings and Crescent City; (f) Eureka; (g) Fort Bragg; (h) San Francisco and Bodega Bay; and (i) Monterey and Morro Bay.

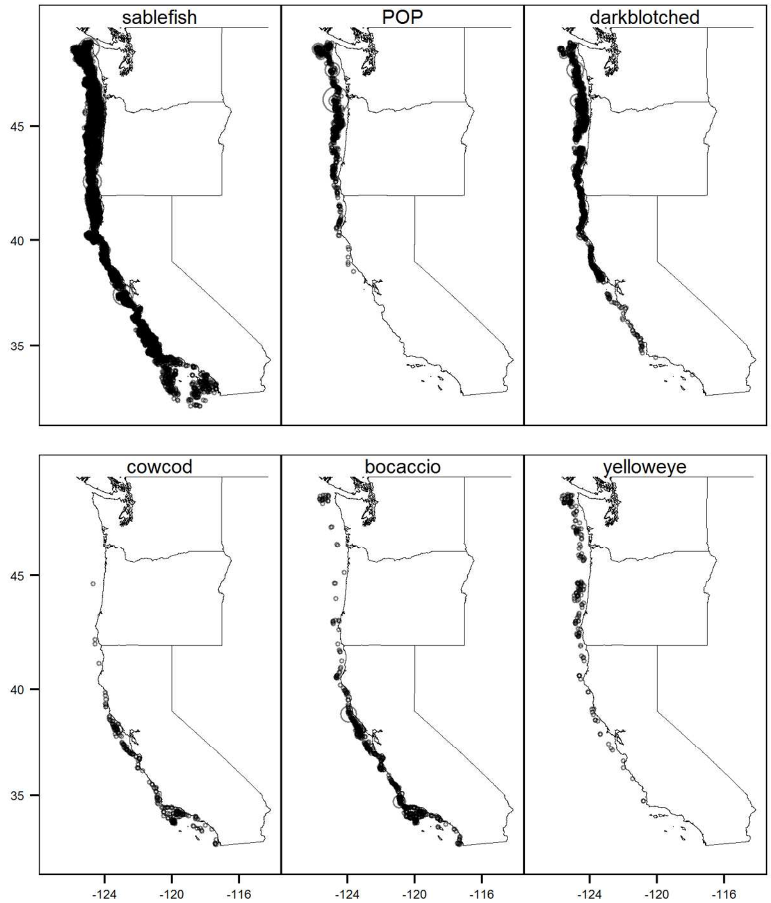

Figure 3. Positive tows (kg) from the Northwest Fisheries Science Center Shelf-slope survey from 2003 to 2014. Panels display data for a single species across all years, where the size of the transparent circle is relative to the species specific weight in a given tow. From left to right, top to bottom, species are: sablefish, Pacific ocean perch (POP), darkblotched rockfish, cowcod, boacaccio, and yelloweye rockfish.

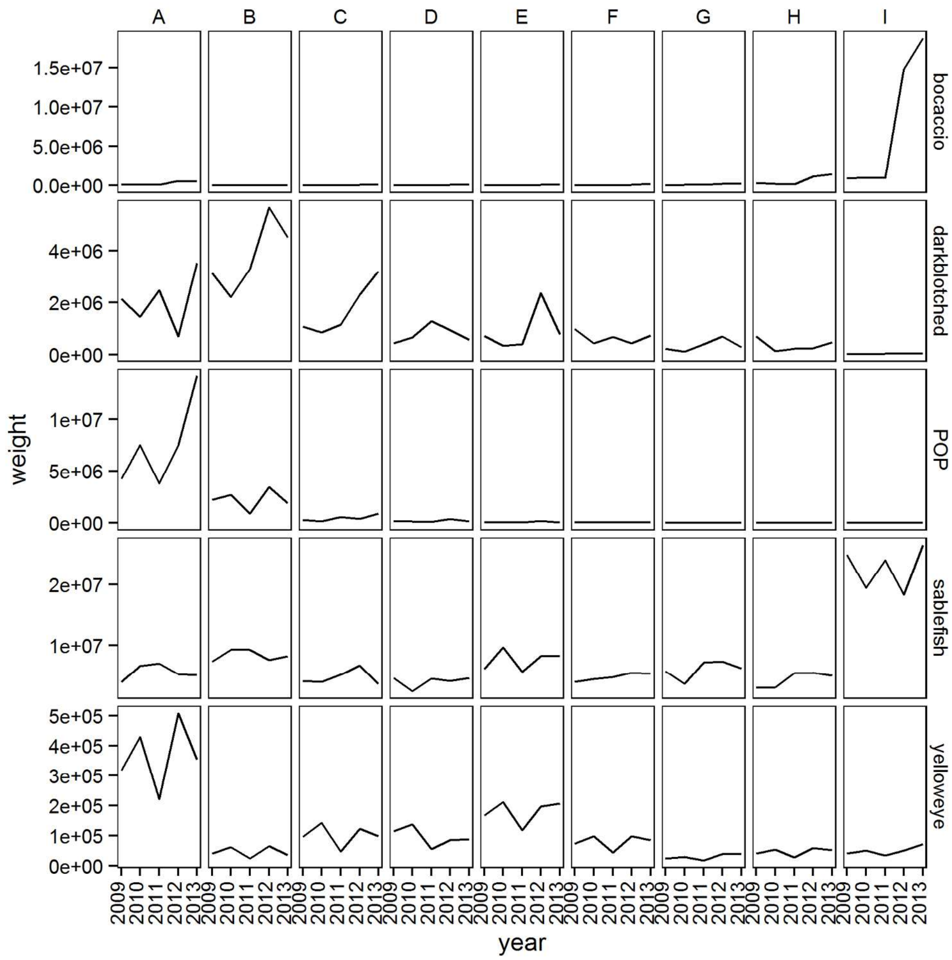

Figure 4. Species specific relative indexes of abundances per port group estimated from delta-generalized linear mixed effects models fit to data from the Northwest Fisheries Science Shelf-slope survey trawl. Nine port groups (columns) along the US West Coast were included from Washington to the southern California Mexico border: (A) Washington, (B) Astoria and Tillamook, (C) Newport, (D) Coos Bay, (E) Brookings and Crescent City, (F) Eureka, (G) Fort Bragg, (H) San Francisco and Bodega Bay, and (I) Monterey and Morro Bay. Results are presented for four overfished species and sablefish (rows). Indices were generated using data from 2002 to 2014, but results are only shown for 2009 to 2013 because those represent the years for which economic data was also available.