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

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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. Switching fishing gear for another gear type with a lower rate of bycatch is often listed as the most feasible method to reduce bycatch. Unfortunately, fishermen are faced with many decisions and when the management framework allows for them to switch gears it is often difficult to predict under what circumstances they will do so. Here, we explored the effects of biological, economic, and societal factors on gear choice using statistical models. The approach was applied to fishery-independent and -dependent data regarding the United States West Coast sablefish fishery. Cluster analysis identified five major changes in gear type: 1986, 1990, 1996, 2004, and 2010 since the enforcement of the first federal regulations in 1982. Subsequently, generalized linear mixed effects models were developed to quantify the effects of biological, economic, and social factors. The application of the model approach highlights the major difficulties of integrating data across multiple disciplines and why it is important to verify all model assumptions. Results are contrasted with models that violate model assumptions to demonstrate the importance of knowing how data was collected and the societal context within which data were generated. Research provides a framework for quantifying gear choice in other fisheries and highlights the need for collecting data on local governance structures, such as membership in and/or rules of risk pools, enabling the quantification of socio-economic drivers of fishermen behaviour.

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

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      1. Data for the case study of US West Coast sablefish fishery used in this analysis were provided at vastly different spatial resolutions. Aggregating the fishery-independent data was necessary, but how to best perform the aggregation still remains unclear. Fishing vessels, particularly commercial trawlers, are highly mobile and capable of fishing in waters off of multiple ports or at multiple depths within a single fishing trip (citation). Consequently, it remains unclear how likely estimated relative indexes of abundance actually characterize true abundances encountered by vessels while fishing. The aggregation method likely misses fine-scale ecological patterns experienced by fishermen. For instance, Heery and Cope (2014) found that trawl fishermen departing from Avila, California fished within a range of less than one degree latitude and species associations for less abundant species were scale dependent.
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      * 1. 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).
        2. 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.
        3. 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).
   3. Contextualization of the model selection results
      1. Models are only characterizations of the real world. Therefore, when building a model one must consider its limitations and make choices leading to trade-offs regarding realism, precision, and generality (Levins, 1966; Dickey-Collas *et al*., 2014).
      2. Without the use of heavy subsidies, decreasing input controls can lead to delays in fleet downsizing and flocking behaviour even if the results are known to be unprofitable (Fulton *et al*., 2011a).
      3. Gear switching can reduce bycatch (FAO, 2010).
      4. 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.
      5. 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).
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         1. The 2015 stock assessment noted a shift in the proportion of landings caught by each fleet. Future catch limits were therefore adjusted, such that instead of assigning the total estimated allowable catch to each fishery based on proportions from the previous x years, proportions were assigned based on the previous x years. If catches are not accurately reported specific to each gear type results from the model will be biased because selectivity patterns differ between gears. Second, if proportions are changing catch limits will be wrong.
      2. Decreased bycatch rates
         1. Bycatch rates are gear specific and when managers allow or specify the use of a new gear it is often under the assumption that bycatch rates will decrease relative to the previously used gear type. Decreased bycatch rates with new gear types are not always fully realized because fishermen may not be accustomed to the new gear or to areas in which the new gear is allowed (Bellman and Heery, 2013).
5. Acknowledgements
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Timeline

2015-12-22 Send outline to core group (Ana, Sarah, Nadine, Kelli)

2015-12-24 Receive feedback on outline

2015-12-29 Send revised Introduction to core group

2015-12-30 Send revised Methods to core group

2015-12-30 Start revising analysis

2016-01-01 Receive feedback on Introduction and Methods

2016-01-08 Send revised Results and Discussion to core group

2016-01-15 Send revised paper to Lorenzo, Mary, and Kathryn

2016-02-05 Submit revision

1 Introduction

Uncertainty is a universal feature of resource management. Although terms differ among disciplines, this uncertainty can be categorized into three broad categories: (a) environmental variation, referring to the natural variability of ecosystems; (2) scientific uncertainty, which arises due to imperfect observations and modelling of ecosystem dynamics; and (3) implementation uncertainty, pertaining to imprecisions in the application of management actions (citation). In fisheries management, all sources of uncertainty can act to undermine effective management frameworks, yet (3) has received far less attention than (1) and (2) (Fulton *et al*., 2011b). Reducing (3) relies on increasing our ability to predict fishermen’s responses to management frameworks, which can be done by: (a) reviewing fishermen behaviour under similar management frameworks and (b) using logic to infer what fishermen will do under untried management policies. Here, we focus on (a) and emphasize the importance of integrating perspectives and data from multiple disciplines.

Fishermen behaviour develops in response to both long- and short-term choices, which are highly contextual (Hart and Pitcher, 1998; Hunt, 2005). For example, long-term choices can include decisions about capital investments, such as purchasing a new vessel, whereas short-term choices can include decisions about a fishing trip, such as whether or not to go fishing. Choices are guided by information on environmental factors, risk tolerance, personal experience, economic expectations, management constraints, etc. (citation). Furthermore, choices are typically weighed against multiple objectives, involve factors with varying levels of uncertainty, and may depend on the actions of other fishermen (Allen and McGlade, 1987). Therefore, fishermen behaviour will be driven by much more than just economic objectives (e.g., profit maximization) and policies that fail to account for this complexity may fail to reach objectives (Mahon *et al*., 2008).

Globally, reducing catch of non-target species and individuals (i.e., bycatch) is a goal of fisheries management (FAO, 1995; Magnuson-Stevens Fishery Conservation and Management Act, 16 U.S.C. § 1802(2)). 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). Regrettably, strategies that offer potential decreases in bycatch may impair other aspects of sustainable fisheries or fishermen livelihoods (Lewison et al., 2011; Senko et al., 2014, Teh et al., 2015). For instance, gear restrictions can be prohibitively costly and per-unit taxes on bycatch, payable by individual fishermen, promote 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). Furthermore, total allowable catch (TAC) policies that guarantee observation of bycatch limits promote inefficiency when quota for profitable species remains unfilled (Androkovich and Stollery, 1994; Holland, 2010; Patrick and Benaka, 2013).

Fishermen typically favour incentive based methods to reduce bycatch (e.g., economic incentives to increase catch utilization) over input controls (e.g., gear restrictions). For example, changing social norms motivated small-scale fishermen of Baja California Sur, Mexico to spatially shift their effort to reduce bycatch of loggerhead sea turtles (Peckham *et al*., 2007) and a desire to fish in parts of the Barents Sea closed due to high bycatch rates prompted trawl fishermen to voluntarily adopt gear modifications (Isaksen *et al*., 1992). 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). Individual transferable quotas (ITQs), where fishermen are allocated shares of the TAC, are theorized to reduce the need for input control measures by encouraging fishermen to change their behaviour in a way that reduces catch of species for which quota is scarce (Casey, 1995; Hall et al., 2000; Holland and Jannot, 2012). Regrettably, it is difficult for managers to determine a priori how fishermen will behave if given the opportunity to alter their behaviour.

This study used cluster analyses and generalized linear mixed effects models (GLMMs) to better understand fishermen behaviour regarding gear choice under key economic, ecological, and socio-cultural drivers, such as fish price, relative abundance, and the presence of an ITQ management framework. The study focused on the United States (US) West Coast sablefish (*Anoplopoma fimbria*) fishery. This fishery underwent major management changes in 2011 with the implementation of an ITQ system and the added ability to switch between trawl, longline, and pot gears, where bycatch rates of overfished species vary between gears (Table 1). While an important socio-ecological assessment (Jenkins and Garrison, 2013) was instrumental in guiding the newly implemented regulations it remains unclear what, if any, of the predicted benefits were realized and if retrospective analyses suggest similar drivers of fishermen behaviour as those foreshadowed by stakeholders during the investigative socio-ecological assessment. The objectives of this study are therefore to: (1) identify and contextualize major changes in fishermen behaviour; (2) develop a framework for quantifying drivers of fishermen behaviour using a wide variety of data collected across multiple disciplines; and (3) discuss challenges of interdisciplinary research, particularly with regard to quantifying socio-economic factors.

2 Methods

2.1 Overview

Multiple methods were used to understand fishermen behaviour in this case study. First, major shifts in gear choices were identified using cluster analysis. Contextualization of these shifts was made possible through a literature search. Second, generalized linear mixed effects models (GLMMs) were used to quantitatively identify likely drivers of fishermen behaviour with respect to gear choice. Fishery-dependent and -independent data were used to build an *a priori* determined set of models to assess the relative contribution of ecological, economic, and social covariates on the proportion of sablefish landings caught by trawl gear. Integrating data collected from multiple disciplines in a single model facilitates analysing fishermen behaviour from a socio-ecological perspective, a necessary step toward sustainable fisheries.

2.2 Case-study background

The US West Coast sablefish fishery is part of a federally managed multispecies (90+) groundfish fishery operating from the US-Canada border in the north to the US-Mexico border in the south (PFMC, 2014). Harvesting occurs both commercially through limited entry, open access, and tribal programs and recreationally through targeted and incidental take. All tribal fisheries are located off the coast of Washington, where tribes have a federal treaty right to fish in their “usual and accustomed” fishing areas. The fishery primarily targets demersal species such as sablefish, Dover sole (*Microstomus pacificus*), shortspine thornyhead (*Sebastolobus alascanus*), Petrale sole (*Eopsetta jordani*), and Pacific whiting (Pacific hake, *Merluccius productus*). Prior to 1982 management was under the jurisdiction of each respective coastal state (i.e., Washington, Oregon, and California). With the implementation of the Magnuson-Stevens Act and the creation of the Pacific Fisheries Management Council (PFMC) Groundfish Fishery Management Plan, management authority switched to the federal government, with the first federal regulation being coast-wide trip limits implemented in October of 1982.

Today, sablefish is one of the most valuable stocks, with values reaching $44.7 million in 2011 (PacFIN, 2015). The sablefish fishery ranges from California to Alaska. The research presented here only focuses on that which operates under the PFMC (i.e., Washington to California), as the Canadian portion operates under the Department of Fisheries and Oceans Canada and the Alaskan portion operates under the North Pacific Fisheries Management Council. Some of the first records of sablefish landings were documented by the California Department of Fish and Wildlife in 1908 (Figure 1; Johnson *et al*., 2015). Prior to 1960, landings were mainly caught using hook and line, with later increases in the 1970s attributed to the development of a foreign vessel pot fishery. Reports of trawl landings also date back to the early 1900s, though trawl landings rarely exceeded those by hook and line until the late 1960s.

The fishery encounters a large number of bycatch species, including Pacific halibut (*Hippoglossus stenolepis*), an internationally managed species, and five overfished species (Table 1): (1) bocaccio (*S. paucispinis*; Field, 2013); (2) cowcod (*S. levis*; Dick and MacCall, 2014); (3) darkblotched rockfish (*S. crameri*; Gertseva and Thorson, 2013); (4) Pacific ocean perch (POP, *S. alutus*; Hamel and Ono, 2011); and (5) yelloweye rockfish (*S. ruberrimus*; Taylor and Wetzel, 2011). Prior to 2011, discarding was allowed, thus bycatch TACs were non-binding. With the 2011 implementation of the ITQ program, TACs for bycatch species vessels were apportioned to individual vessels based on bycatch rates applied to target species TACs (PFMC and NMFS, 2010). Furthermore, TACs of bycatch species became binding and gear switching was implemented.

More social information on the fishery here.

2.3 Determination of dominant transition points

Dominant transition points, or time periods, when a given gear type accounted for a large portion of US West Coast sablefish landings were identified using hierarchical clustering. Clusters were defined using nearest neighbour-chain algorithms within the R statistical environment (stat::hclust; R Core Team, 2015), which minimize variance using a “complete” “bottom up”, or agglomerative, criterion. Cluster analyses were conducted for reported catches of sablefish trawls, pots, and longlines from 1982, the first year of federal management, to 2014, the last year of available catch data. Resulting dendrograms were plotted within R. Guided by estimated transition points, an extensive literature search provided insight into the fishery dynamics which characterized transitions between dominating gear types.

2.4 Generalized linear mixed effects models

Generalized linear mixed effects models (Pinheiro and Bates, 2000) were used to identify the extent to which proportions of sablefish landings caught by trawl gear are associated with covariates. GLMMs are extensions of linear models with an added random component providing the flexibility needed to model statistical means of hierarchical data, which lack independence, and their variance and covariance. Here, random effects were included for port groups, the spatial resolution to which all data was aggregated (see below for more details on spatial resolutions of each data set). Analyses were performed using the Generalized Additive Models for Location, Scale, and Shape (gamlss) package (Rigby and Stasinopoulos, 2005) in R. 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.

The dependent variable, proportion of port group specific sablefish 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, and (Beta(1, 1) is equivalent to a uniform distribution), , where is a normalization constant defined via Euler’s Γ function, . The Beta distribution cannot model non-uniform densities with probability mass at zero or one. The data included a non-negligible number of ones, thus a one-inflated Beta distribution, a mixed continuous-discrete distribution with an additional parameter, , that allows ones, was used (Ferrari and Cribari-Neto, 2004). Thus, , represents the case where .

Independent variables were hypothesized to be large-scale sectors that influence fisheries, such as markets and management frameworks. Here, we refer to these large-scale sectors as ‘drivers’ and the metrics by which to measure or identify the drivers as ‘variables’. To guide the identification of possible drivers of fishermen behaviour we used the four subsystems defined in Ostrom’s (2009) social-ecological system framework for common pool resources: (1) resource systems (e.g., a marine protected area), (2) resource units (e.g., fish), (3) governance systems (e.g., TAC or ITQ frameworks), and (4) users (e.g., fishermen and cannery operators). Variables (described below) were selected based on relationships to drivers identified using Ostrom’s (2009) four subsystems, data availability, and hypothesized significance to this case study (Table 2). Many variables were correlated. Consequently, factor analysis with orthogonal axis rotation in R () was used to create a set of non-correlated factors that retain the predictive relationships of the original variables. Factors with eigenvalues greater than one, along with categorical variables coding governance phases and port group, were carried forward (Table 2).

Resource system. 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. PacFIN data were provided as port specific measures summed by the port group ((1) Washington, (2) Astoria and Tillamook, (3) Newport, (4) Coos Bay, (5) Brookings and Crescent City, (6) Eureka, (7) Fort Bragg, (8) San Francisco and Bodega Bay, and (9) Monterey and Morro Bay) at which they were landed. Port specific measures were not provided 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 (16 U.S.C. § 1881a).

User. Data on vessel characteristics have been 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. EDC data were provided as port specific measures averaged by port group (same nine groups as above). Data from each vessel was assigned to a single port group, even though they may deliver to multiple port groups in a single year, based on the port group for which that vessel had the highest ex-vessel revenue for that year. Same as above, no data were provided where there were not enough observations to ensure confidentiality.

Resource unit. Relative indexes of abundance for each overfished species and sablefish were included as an indicator of that species’ ecological status. Spatially explicit relative indexes of abundance for sablefish and four overfished species were estimated using delta generalized linear mixed-effects models (delta-GLMMs), which can account for vessel “catchability”, spatiotemporal variability, and uncertainty arising from small sample sizes or extreme catch events, implemented with an open source software package (Thorson and Ward, 2013) in R. Although cowcod is currently declared overfished, it was not included because spatial management (Rockfish Conservation Areas) has been successful in decreasing instances of bycatch and as a species they represent the smallest (sometimes zero) percent of bycatch within the sablefish fishery (NMFS, 2004).

Data included spatially resolved (trawl mid-point) fishery-independent species-specific catches collected by the Northwest Fisheries Science Center (NWFSC) Shelf-Slope survey, which collects annual data on hundreds of fish species along the US West Coast (Bradburn *et al*. 2011). Contracted commercial fishing vessels conduct standardized bottom trawl surveys at depths of 55 to 1280 m from Cape Flattery, Washington (48° 10’N) to the US-Mexico border (32° 30’N). Typically the survey contracts four vessels per year, although 2012 involved 2 contracts to a single vessel. The entire survey area is usually covered twice per year using a stratified random sampling design (based on three depth categories), with sampling extending from late May to late July for the first pass and from mid-August to late October for the second pass. Data are used as the primary source of abundance information for most PFMC groundfish stock assessments.

Delta-GLMMs facilitate the inclusion of vessel:year interactions as random effects, which is necessary because vessels were not consistent across years (Helser *et al*., 2004). Gamma error structures 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. Stratam were defined according to latitudinal 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 with fishing out of major ports (see nine major ports as listed above) and prominent biogeographic features at Cape Blanco, OR (42° 50`N) and Cape Mendocino, CA (40° 26`N). 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).

Governance system. Governance phase changes were identified through an extensive literature search and hierarchical cluster analysis. Restricted access measures to permits and quota were of particular interest because of their role in shifting effort and allowing fishermen to change or modify their gear. Therefore, the included time series was divided into distinct phases marked by particular formal governance events (Table 4).

Continuous fixed effect covariates were z transformed, ()), 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).

2.5 Model selection

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, where denotes sample size, is the number of parameters, and is the maximized likelihood of the model. 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).

2.6 Violation of model assumption

Additional models were explored that ignored random effects, vessel specific effects related to indexes of abundance, ….

3 Results

3.1 Dominant transitions

Transitions were identified at …

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.

3.2 Generalized linear mixed effect models

3.3

4 Discussion

5 Acknowledgements

This publication was partially funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No. ??, Contribution No. ?? and The National Science Foundation (NSF) under ??. KFJ was partially supported for this work by a grant from Washington Sea Grant, University of Washington, pursuant to National Ocean and Atmospheric Administration Award No. NA14OAR4170078. SK was partially supported for this work by the Social Sciences and Humanities Research Council of Canada Grant F12-04439. AKS was partially supported for this work by the Smithsonian Tropical Research Institute and the Panamanian National Secretariat for Science, Technology and Innovation. NH was partially supported for this work by a Coastal SEES NSF grant. The authors thank Erin Steiner and Beth Horness for providing data, Todd Lee for his initial insights, and the organizers and participants of the 2014 Transdisciplinary Academy in Marine Resource Sustainability for discussions and advice prior to the completion of this manuscript. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its sub-agencies.

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

Table 2. Hypothesized drivers of fishermen behaviour with respect to gear choice within the US West Coast sablefish fishery. Variables are linked to drivers and belong to a given system according to Ostrom’s (2009) social-ecological system framework for common pool resources. All dollars are reported in USD. Groupings from factor analysis are reported along with their associated eigenvalues in parenthesis. Only factors with an eigenvalue greater than one were carried forward to the generalized linear mixed effect models.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| variable | driver | system | source | factor analysis | interpretation |
| bocaccio | ecosystem | resource units | NWFSC survey |  |  |
| darkblotched rockfish | ecosystem | resource units | NWFSC survey |  |  |
| Pacific ocean perch | ecosystem | resource units | NWFSC survey |  |  |
| yelloweye rockfish | ecosystem | resource units | NWFSC survey |  |  |
| fuel ($) |  |  |  |  |  |
| ex-vessel ($·lb-1) |  |  |  |  |  |
| ITQ | management | governance |  | categorical |  |

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 |

Table 4. Governance phases.

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

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

Table 4. Model coefficient results for the most parsimonious model (biology). 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). The second parameter of the beta distribution (*b*) is modelled using a log link, rather than logit, and thus exp(*b*) should be interpreted as the mean of the *b* amongst port groups. 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 |

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 |

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

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.